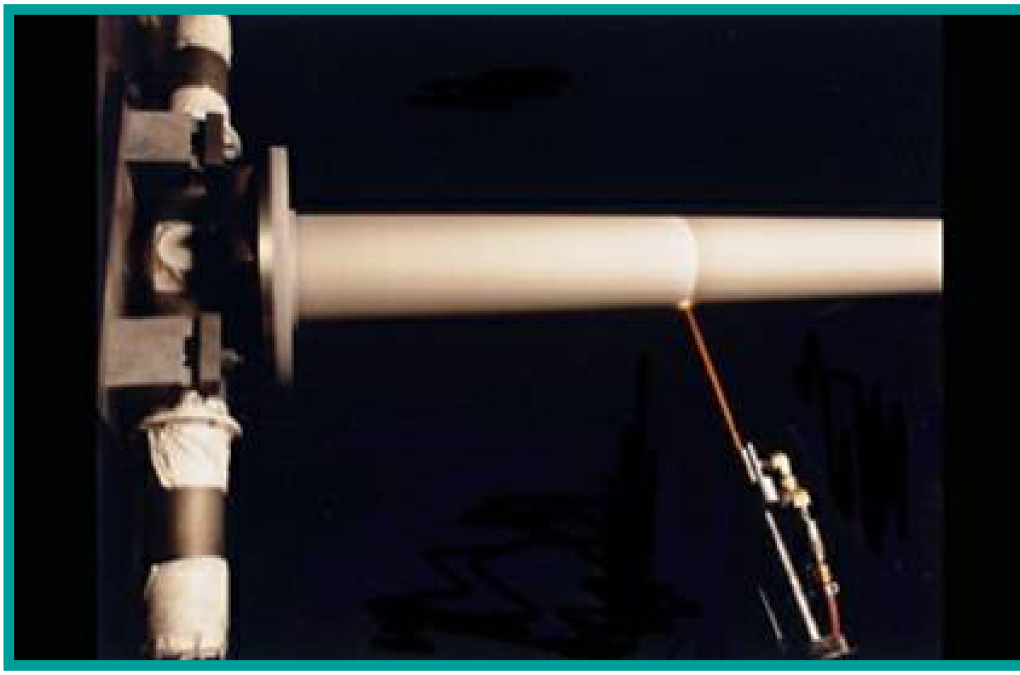
ESTCP
Cost and Performance Report

(WP-0038)



Validation of HVOF Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Hydraulic/Pneumatic Actuators

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ESTCP Project: WP-0038

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ALC	Air Logistics Center
AF	Air Force
AFB	Air Force Base
AMS	Aerospace Materials Specification
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BAC	Boeing Aircraft Corporation
BMS	Boeing Materials Specification
CAA	Clean Air Act
CBA	cost/benefit analysis
CFR	Code of Federal Regulations
CITE	Center of Industrial and Technical Excellence
CWA	Clean Water Act
DARPA	Defense Advanced Research Projects Agency
DI	Deionized
DoD	Department of Defense
ECAM	Environmental Cost Analysis Methodology
EHC	electrolytic hard chrome
EPA	Environmental Protection Agency
ESOH	environment, safety and occupational health
ESTCP	Environmental Security Technology Certification Program
FPI	fluorescent penetrant inspection
FTE	full-time equivalent
GEAE	GE Aircraft Engines
GTE	gas turbine engine
HA	hydraulic actuator
HCAT	Hard Chrome Alternatives Team
HEPA	high-efficiency particulate arresting
hex-Cr	hexavalent chromium
HV	Vickers hardness number
HVOF	high-velocity oxygen-fuel
IARC	International Agency for Research on Cancer
ID	internal diameter
IRR	internal rate-of-return
JG-PP	Joint Group on Pollution Prevention
JTP	joint test protocol

ksi	thousands of pounds per square inch
MRO	maintenance, repair and overhaul
NADEP-CP	Naval Air Depot Cherry Point
NADEP-JAX	Naval Air Depot Jacksonville
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NDI	non-destructive inspection
NLOS	non-line-of-sight
NPV	net present value
OC-ALC	Oklahoma City Air Logistics Center
OD	outside diameter
OEM	original equipment manufacturer
OO-ALC	Ogden Air Logistics Center
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PEWG	Propulsion Environmental Working Group
PPE	personal protective equipment
PRCA	pitch/roll channel assembly
psi	pounds per square inch
PTFE	designation for Teflon
QC	quality control
Ra	arithmetic average surface roughness
RCRA	Resource Conservation and Recovery Act
Rp	maximum peak height in surface profile
rpm	rotations per minute
Rz	10-point average of highest peaks and lowest valleys
S/N	stress vs. number of cycles (for fatigue data plots)
SAE	Society of Automotive and Aerospace Engineers
T-400	Tribaloy 400
TO	technical order
Tp	bearing ratio in surface profile
TRI	toxic release inventory
TWA	time-weighted average
UTS	ultimate tensile strength

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Electrolytic hard chrome (EHC) plating is a technique that has been in commercial production for over 50 years. It is a critical process that is used both for applying hard coatings to a variety of aircraft components in manufacturing operations and for general re-build of worn or corroded components that have been removed from aircraft during overhaul. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr or Cr^{6+}) being a known carcinogen. During operation, chrome plating tanks emit a hex-Cr mist into the air, which must be ducted away and removed by scrubbers. Wastes generated from plating operations must be disposed of as hazardous waste and plating operations must abide by U.S. Environmental Protection Agency (EPA) emissions standards and Occupational Safety and Health Administration (OSHA) permissible exposure limits (PEL).

High-velocity oxygen-fuel (HVOF) thermal spray technology can be used to deposit both metal alloy coatings and ceramic/metals (cermets) such as tungsten carbide/cobalt (WC/Co) that are dense and highly adherent to the base material. Previous research, development and validation efforts had established HVOF thermal spray coatings as the leading candidates for replacement of hard chrome. This led to industry acceptance of HVOF WC/CoCr and WC/Co in place of hard chrome for landing gear, to the point that landing gear on most new aircraft designs are now specified with HVOF. In addition, in overhaul operations these coatings can be built up to thicknesses needed for dimensional restoration, as is currently done with EHC.

HVOF systems are commercially available and installed in several depots, and there are numerous commercial vendors supplying the OEM community. Although HVOF coatings are now coming into wide use for landing gear, their qualification as an acceptable replacement for EHC plating on actuators has not been adequately demonstrated. The Hard Chrome Alternatives Team (HCAT) was formed to perform the demonstration/validation for the HVOF coatings.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives were to demonstrate, through coupon materials testing, functional rig testing and delta qualification testing of actual hydraulic actuators, that HVOF coatings have equivalent or better performance than EHC coatings.

1.3 REGULATORY DRIVERS

EHC plating operations must comply with 40 Code of Federal Regulations (CFR) Part 63 (National Emissions Standards for Hazardous Air Pollutants) and 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards). In February 2006 OSHA promulgated a new Cr^{6+} PEL of 5 $\mu g/m^3$, with an Action Level of 2.5 $\mu g/m^3$, an order of magnitude below the previous standard of 52 $\mu g/m^3$. A Navy/Industry task group concluded in a 1995 study [1] that the cost of compliance for all Navy operations that utilize hex-Cr (i.e., not just plating) would be about \$5 million annually at a PEL of 5 $\mu g/m^3$. Air sampling by the Navy showed that a very large number of operations, including chrome plating, painting and depainting, sanding and

corrosion control, would all exceed the Action Level – some by a wide margin. The costs of meeting the PEL are likely to be very high at some Department of Defense (DoD) facilities.

1.4 DEMONSTRATION RESULTS

For materials testing, substrates were 4340 high strength steel, (180-200 ksi ultimate tensile strength (UTS)), PH15-5 stainless steel (155 ksi UTS) and Ti-6Al-4V (130 ksi UTS). HVOF coatings were WC/10Co4Cr, Cr_3C_2/20(80Ni-20Cr) and Tribaloy 400 (T-400, nominal composition 57Co-28.5Mo-8.5Cr-3.0Ni-3.0Si)

- ❑ Fatigue: All HVOF coatings on 4340 and PH15-5 steel were equal to or better than EHC, with T-400 having significantly better fatigue. There was some cracking of the HVOF coatings at the highest loads as well as at the highest cycles. Spalling of the HVOF coatings occurred on 4340 at the highest load (160 ksi) and at the highest cycles (9.5 million cycles). There was cracking, but no spalling, on the PH15-5 specimens. The data on Ti-6Al-4V were unreliable since neither the EHC nor the HVOF coatings adhered properly.

- ❑ Salt Fog Corrosion (ASTM 1,000 hour B117): As in previous tests, the EHC coatings in general provided somewhat better appearance rankings than HVOF coatings. Thicker EHC or HVOF coatings did not in general provide any better protection. Both rods and flat panels were evaluated, with no consistent performance differences between them. Previous HVOF EHC replacement projects determined that there is very poor correlation between the standard B117 cabinet testing of HVOF and EHC coatings and their actual performance in atmospheric exposure and in service. Since the B117 corrosion behavior on the substrates in this testing is similar to what has been observed in other evaluations, it is expected that the service performance of HVOF coatings on these substrates is likely to be at least equivalent and probably better than that of EHC.

- ❑ Fluid Immersion: The coatings were tested for weight loss and roughening in a wide variety of commonly-used cleaners, etchants, hydraulic fluids, fuels and other chemicals likely to be encountered during repair/overhaul or in service. WC/CoCr and Cr_3C_2/NiCr were not affected by any of these chemicals, while T-400 showed slight attack by strong cleaners and reactive chemicals. The one exception was that the Co-containing coatings, WC/CoCr and T-400, were both strongly attacked by bleach (sodium hypochlorite). Bleach is not used in repair, but is sometimes used as a disinfectant on commercial aircraft during disease outbreaks. Cr_3C_2/NiCr was unaffected.

- ❑ Environmental Embrittlement (200 hour ASTM F519): None of the coatings, including EHC, caused environmental embrittlement (re-embrittlement) in DI water or 5% NaCl solution.

- ❑ Functional Rod-Seal Testing: Testing was run by NAVAIR Patuxent River, using HVOF WC/CoCr with different surface finishes, using actuator speeds and temperatures intended to simulate service conditions. Several seals from different

manufacturers were tested – O-ring with capstrip, O-ring with two backup rings, fluorosilicone O-ring with PTFE cap and spring energized PTFE. In almost all cases the HVOF coatings gave significantly less leakage than the EHC, the only exception being a seal system of an O-ring with two backups, where the performance of HVOF and EHC was the same. Surprisingly, the ground (not superfinished) rods had the least leakage of all. However, the surface on the ground coatings did smooth out over time, whereas the superfinished rods showed only very faint scratches. The EHC coated rods showed considerable scratching. There was very little seal damage especially when using superfinished HVOF coatings. Overall the best performance was for a superfinished HVOF-coated rod with either a MIL-P-83461 O-ring with PTFE cap strip or spring energized PTFE seals with backup ring.

- Component Testing and Qualification: Testing of actuators with HVOF WC/CoCr-coated rods was carried out by the Oklahoma City Air Logistics Center Airborne Accessories Directorate Avionics and Accessories Division (OC-ALC/LGERC). Flight control actuators, utility actuators and snubbers were tested, with test components chosen to permit qualification of additional components by similarity. Overall, actuators with HVOF-coated rods were found to perform as well as or better than those with EHC-coated rods, although in some cases different seals were required. A number of actuators have passed rig tests and are going into service testing. Actuators tested were: C130 Rudder Booster Actuator, A-10 Aileron Actuator, C/KC-135 Aileron Snubber (passed testing, to be service tested); B-1 Horizontal Stabilizer (endurance testing successful, no service tests needed, drawings updated, Tech Order and stocklist updates in progress); B-1 Pitch/Roll SCAS (testing in progress); F-15 Pitch/Roll Channel Assembly (to be tested); T-38 Aileron (testing successful); C-130 Ramp and C-KC-135 Main Landing Gear Actuators (passed testing with change to seal specification, to be service tested); C/KC-135 Main Landing Gear Door (qualified for service testing).

1.5 COST/BENEFIT ANALYSIS (CBA)

A CBA was conducted at a facility that overhauls aircraft components including landing gear and actuator components. For the combined landing gear and actuator workload the analysis predicted a 15 year net-present-value (NPV) of $18 million, which rose to $25 million when performance improvements were added. Taking into account the new OSHA Cr^{6+} PEL raised the payback slightly, but a major contributor to economic payback is the improved performance afforded by HVOF, which reduces the need for stripping and replacing coatings. This also directly reduces waste streams.

1.6 STAKEHOLDER/END-USER ISSUES

HVOF coatings on actuator rods will generally work better than EHC, with less leakage and lower wear of both rod and seal. However, the rod should be superfinished and the seal may need to be changed to an energized PTFE design.

During the most recent European outbreak of hoof-and-mouth disease, aircraft wheels were sprayed with bleach to inhibit the spread of the disease. Test results clearly showed that bleach will dissolve Co-containing coatings such as WC/CoCr, which could lead to fluid loss, seal damage, or even stress-corrosion cracking. An alternative disinfectant should be used in place of bleach for aircraft landing gear, wheels and brakes.

It is clear from testing performed in this project that if Ti alloys are to be HVOF-coated they should be grit blasted, although this should probably be done at an angle and at a lower pressure than usual to avoid embedding grit. This is in accord with current industry practice on components such as titanium flap tracks.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Technology background and theory of operation: High-velocity oxygen-fuel (HVOF) is a standard commercial thermal spray process in which a powder of the material to be sprayed is injected into a supersonic flame of a fuel (usually hydrogen, propylene or kerosene). The powder particles are accelerated to high speed and soften in the flame, forming a dense, well-adhered coating on the substrate (see Figure 1). The coating material is usually a metal or alloy (such as Tribaloy or stainless steel), or ceramic particles in a metal matrix, designated a cermet (such as cobalt-cemented tungsten carbide, WC/Co). The technology is used to deposit coatings about 0.003" thick on original equipment manufacturer (OEM) parts, and to rebuild worn components by depositing layers up to 0.015" thick.

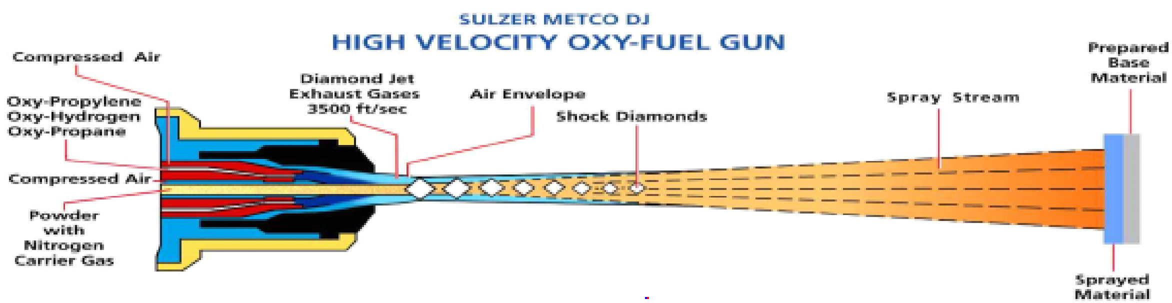

Figure 1. Schematic of HVOF Gun and Process (Sulzer Metco DiamondJet).

Applicability: HVOF was originally developed primarily for gas turbine engine (GTE) applications. The primary thermal spray processes are flame spray, plasma spray, arc spray, HVOF and the recently-developed cold spray. The original high velocity spray technology was the pulsed deposition detonation gun (D-gun) developed by Union Carbide (later Praxair). The quality of the wear and erosion resistant spray coatings produced by this method was much better than the lower speed methods, and continuous flame HVOF was developed as a competitive response.

The original applications for HVOF were wear components in GTEs, such as shafts and bearing journals. As the availability and use of the technology grew, it began to be applied to a wide range of other types of coatings and applications, including a variety of aircraft components such as flap and slat tracks, landing gear and hydraulics for commercial aircraft. It is now being used in many applications outside the aircraft industry, such as industrial rolls and vehicle hydraulics. The original aircraft wear applications, primarily used by Boeing, were for otherwise-intractable spot problems that neither the original alloy nor chrome plate could solve.

The technology can be used to spray a wide variety of alloys and cermets. It is limited for high temperature materials such as oxides, most of which cannot be melted in the flame. The areas to be coated must be accessible to the gun – i.e., they must be line-of-sight.

Material to be Replaced: HVOF coatings are used to replace EHC plating (especially using carbide cermets and high temperature oxidation-resistant Tribaloys). The combination of HVOF NiAl with an overlayer carbide is also used to replace the combination sulfamate Ni/hard chrome. HVOF coatings can also be used to replace some hard Ni and electroless Ni coatings on such components as flap tracks and propeller hubs. In the HCAT program the primary application is hard chrome replacement.

2.2 PROCESS DESCRIPTION

Installation and Operation: The HVOF gun can be hand-held and used in an open-fronted booth. However, the supersonic gas stream is extremely loud and requires that the operator use very good ear protection. For this reason the unit is usually installed on a six-axis robot arm in a sound-proof booth, programmed and operated remotely. Most depots already use this type of booth for their existing plasma spray operations. Since the method is frequently used for cylindrical items, the most common arrangement is to rotate the component on a horizontal rotating table and move the gun up and down the axis. This is illustrated in Figure 2 which shows the HVOF spraying of a landing gear inner cylinder. A similar setup would be used for the spraying of hydraulic actuator piston rods.

Figure 2. HVOF Spray of Landing Gear Inner Cylinder.

Facility Design: The installation requires:

- A soundproof booth. Booths are typically 15 feet square, with a separate operator control room, an observation window and a high-volume air handling system drawing air and dust out of the booth through a louvered opening.
- Gun and control panel. The gun burns the fuel and oxygen inside its combustion chamber and injects the powder axially into the flame. The gas exits the gun at supersonic speed, while the particles are accelerated to high velocity but usually remain subsonic. The control panel controls the gas flows, cooling water, etc.
- Powder feeder. Powder is typically about 60 μm in diameter and is held in a powder feeder, which meters the powder to the gun at a steady rate, carried on a gas stream. Two powder feeders are commonly used to permit changeover from one coating to another without interrupting the spraying.
- 6-axis industrial robot and controller. Most installations use an industrial robot to manipulate the gun and ensure even spraying. The robot is often suspended from above to leave the maximum possible floor space for large items.

- Supply of oxygen. This is frequently a bulk storage container outside the building. Alternatively, bottled gas can be used but, because of the high usage rate of up to 2,000 scfh, even a standard 12-bottle setup lasts only a few hours in production.
- Supply of fuel gas or kerosene (bottled or bulk). Hydrogen is the most common fuel, supplied in bulk or in bottles. Praxair TAFA guns use kerosene, which is significantly cheaper and less dangerous. There are also systems that utilize natural gas which is considerably less expensive.
- Dust extractor and bag-house filter system. The air extracted from the booth is laden with overspray – particles that have failed to stick to the surface (often 20-50% of the total sprayed). The air is blown into a standard bag house, often located outside the building, where the dust is removed.
- Dry, oil-free compressed air for cooling the component and gun. Air cooling prevents the components being overheated (temperatures must be kept below about 400°F for most high strength steels).
- Water cooling for gun. Not all guns are water cooled, but most are.

Performance: HVOF guns deliver about 4-5 kg of material per hour, of which 65% typically enters the coating, for a coating rate of about 3 kg/hour. For a common 0.010”-thick WC/Co rebuild coating (which will be sprayed to a thickness of 0.013”-0.015” and ground to final dimension), an HVOF gun can deposit about 900 in^2/hr. This permits the coating of the outside diameter of a 25”-long, 4”-diameter cylinder in about 30 minutes, compared with about 12 hours for chrome plating.

Specifications: The following specifications and standards apply to HVOF coatings:

- Prior to the HCAT program, the only aerospace specifications were those issued by OEMs such as Boeing, whose BAC 5851 thermal spray specification, supported by BMS 10-67G powder specification, is still one of the most quoted standards
- Aerospace Materials Specification (AMS) 2447 was developed with the assistance of the HCAT team and issued by SAE in 1998. It is now a widely used standard in the aerospace industry.
- In order to provide specifications for spraying high strength aircraft steels at depots and vendors, HCAT has worked through the Society of Automotive and Aerospace Engineers (SAE) to promulgate several standards:
    - AMS 7881 is a powder specification for WC/Co and AMS 7882 is a powder specification for WC/CoCr that were both issued in April 2003.
    - AMS 2448 is a specification describing procedures for spraying WC/Co and WC/CoCr coatings using HVOF onto high-strength steel that was issued in August 2004.

AMS 2449 is a specification describing procedures for low-stress grinding of HVOF WC/Co and WC/CoCr coatings that was issued in August 2004.

Training: Just as plating shops typically have several personnel who handle masking, racking, demasking, etc., it is common for HVOF shops to have 3 or 4 technicians dedicated to masking and spraying. HVOF training is essential and is usually provided by equipment vendors such as Praxair and Sulzer Metco. Training is also available through the Thermal Spray Society. Depot personnel taking part in the HCAT program have been trained by Jerry Schell, a thermal spray coatings expert at GE Aircraft Engines (GEAE). Since thermal spray is a more complex technology than electroplating, plating line personnel cannot be transferred successfully to an HVOF shop without extensive retraining.

Health and Safety: The process does not produce air emissions or toxic wastes. Co powder is an International Agency for Research on Cancer (IARC) Group 2B material, which means that "The agent (mixture) is possibly carcinogenic to humans", whereas Cr^{6+} is an IARC Group 1 material, "Known to be carcinogenic to humans". However, the OSHA PEL for Co (8hr TWA) of 100 $\mu g/m^3$ is lower than the 1000 $\mu g/m^3$ for metallic chromium, but is substantially higher than the current 5 $\mu g/m^3$ for Cr^{6+}. Unlike chrome plating, the Co is not emitted into the air. Excess Co-containing powder is drawn from the spray booth and captured in the bag house. Nevertheless personnel should wear a dust respirator when handling the powder, working in the booth, or grinding the coating. While the powders are usually about 60 µm in diameter, they can break apart on impact, producing 10 µm or smaller particles. The American Welding Society recommends the use of a respirator complying with American National Standards Institute (ANSI) Z88.2.

Ease of Operation: Since in commercial systems the entire system is programmable, including the gun control and robot, it is generally easy to operate. The operator must create masking (usually shim stock shadow masks) and must develop the correct spray parameters and gun motions. While vendors supply standard operating conditions for different materials, these may have to be optimized experimentally for new materials and powders, and must be adjusted for different components to ensure proper coating speed and gun traverse rate. Small diameter components, for example, must be rotated faster than large ones to maintain the same deposition rate and coating structure. In this respect operating an HVOF system is considerably more complex than electroplating.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Prior to the HCAT program, HVOF technology had been successfully used by Boeing for a number of years for their commercial aircraft and by GEAE for GTEs. In the period 1993-1996 Keith Legg, Bruce Sartwell, GEAE, Cummins Diesel, and Corpus Christi Army Depot carried out an evaluation of chrome alternatives funded by the Defense Advanced Research Projects Agency (DARPA). The program evaluated HVOF, physical vapor deposition (PVD) and laser cladding, and concluded that HVOF was the best overall alternative for use in depots and most OEM aircraft applications [2]. At the beginning of the HCAT program, Lufthansa successfully completed flight tests of HVOF coatings on commercial landing gear and Delta began to carry out similar flight tests.

The HCAT Program was initiated in 1996 and has completed three projects related to demonstration/validation of HVOF thermal spray coatings on landing gear, propeller hub and gas turbine engine components. Joint test protocols were developed for each project and extensive materials testing was conducted on coated materials relevant to the type of aircraft component. Different types of component testing were also conducted. All of the results are presented in final reports [3, 4, 5] and they generally showed that HVOF WC/17Co coatings provide performance at least equivalent and generally superior to EHC coatings. HVOF coatings are now being implemented in production at several DoD repair depots on all three types of components.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Replacing hard chrome plating is a great deal more complex than simply putting down a hard coating. The alternative must not only work technically, but it must fit with the entire life cycle of use and maintenance, and it must be a reasonable, mature technology for depot use. The advantages and limitations of HVOF are summarized in Table 1.

Table 1. Advantages and Limitations of HVOF Thermal Spraying as a Chrome Replacement.

Advantages/Strengths	Disadvantages/Limitations
Technical:	
Higher hardness, better wear resistance, longer overhaul cycle, less frequent replacement	Brittle, low strain-to-failure – can spall at high load. Issue primarily for carrier-based aircraft
Better fatigue, corrosion, embrittlement	Line-of-sight. Cannot coat IDs
Material can be adjusted to match service requirements	More complex than electroplating. Requires careful quality control
Depot and OEM fit:	
Most depots already have thermal spray expertise and equipment	WC/Co requires diamond grinding wheel. Only HVOF alloys can be plunge ground
Can coat large areas quickly	
Can be chemically stripped	
Many commercial vendors	
Environmental:	
No air emissions, no high volume rinse water	Co toxicity

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Performance objectives established for this project consisted of materials testing performed on coupons manufactured from the same base materials from which EHC-plated hydraulic actuator (HA) components are fabricated, functional rod/seal testing to evaluate the performance of HVOF coatings sliding against actual actuator seal materials, and component qualification testing. The objectives were established by the following stakeholders in the project:

- NAVAIR Patuxent River
- NADEP Jacksonville
- NADEP Cherry Point
- Oklahoma City ALC (Cognizant AF Engineering Authority for actuators)
- Ogden ALC
- Propulsion Environmental Working Group (PEWG)
- Boeing Long Beach
- Parker Hannifin
- Smiths Aerospace Actuation Systems
- Shamban Aerospace Seals
- HR Textron
- Moog Aircraft Group
- Saint-Gobain Performance Plastics
- Greene Tweed & Co.
- CoorsTek

Coordination of the project was provided by the Naval Research Laboratory and Rowan Technology Group.

An analysis was first conducted of the components from various actuators used in DoD aircraft onto which EHC is currently applied. Then the stakeholders analyzed the types of conditions under which the EHC-coated components were subjected (e.g., cyclic stresses, sliding wear, corrosion). From these analyses the materials testing requirements were established. A stakeholders meeting was held in October 2003 in Los Angeles to discuss the testing requirements and create an outline of a Joint Test Protocol (JTP). A first draft of the JTP was produced by the project coordinators and was distributed to the stakeholders. There were numerous revisions generated through electronic correspondence, with a final version [6] approved by the stakeholders in March 2004. The specific types of materials testing delineated in the JTP were axial fatigue, salt-fog corrosion, fluid immersion and environmental embrittlement. A detailed description of these tests can be found later in this section. The performance objectives, also called acceptance criteria, were as follows:

- Fatigue: Cycles-to-failure at different stress or strain levels were measured for fatigue specimens coated with either EHC or a thermal spray coating. These data were plotted with stress/strain on the vertical axis and cycles-to-failure on the horizontal axis and smooth curves were fit to the data points. If the curves for the

thermal spray coatings fell on or above those for the EHC, then the thermal spray coatings were considered to have passed the acceptance criteria. The results showed that all HVOF coatings on 4340 and PH15-5 steel passed the acceptance criteria. Results on Ti-6Al-4V were unreliable since neither the EHC nor the HVOF coatings adhered properly.

- Corrosion: American Society for Testing and Materials (ASTM) B117 salt-fog exposure tests were conducted on specimens coated with EHC and various thermal spray coatings. Protection ratings were determined in accordance with ASTM specifications. If the average ratings for the thermal spray coatings were greater than or equal to those for EHC, then the thermal spray coatings were considered to have passed the acceptance criteria. In general, the corrosion performance of the EHC coatings exceeded that of the HVOF coatings, so the acceptance criteria were not met.
- Fluid immersion: Disk specimens fabricated from 4340 steel were coated with different HVOF thermal spray coatings and then were immersed in different types of fluids commonly used in manufacturing and repair operations. If there was no visible attack or weight loss on the coatings, then they were considered to have passed the acceptance criteria. It was determined that the coatings passed the acceptance criteria except for immersion in bleach, which attacked the cobalt-containing coatings.
- Standard ASTM F519 embrittlement specimens were coated with HVOF thermal spray coatings and then immersed in either deionized water or a 5% NaCl solution. If the specimens survived 200 hours of loading without fracture, then they were considered to have passed the acceptance criteria None of the coated specimens fractured, so the acceptance criteria was met.

Also discussed at the October 2003 meeting was execution of functional rod/seal tests using a test rig located at NAVAIR Patuxent River. These tests were intended to simulate the action of a piston sliding against actual seals using in aircraft actuators. The acceptance criteria for these tests were that the fluid leakage, seal wear and coatings wear using HVOF thermal spray coatings on the rods all had to be equal to or less than that when using EHC on the rods. Results of the testing showed that the acceptance criteria was met.

3.2 SELECTION OF TEST FACILITY

The Air Force was the most proactive service involved in the project. Within the Air Force (AF), most hydraulic actuator components are overhauled at the Ogden Air Logistics Center (OO-ALC) which is also where most AF landing gear components are overhauled. Because of this and because HVOF technology is being implemented there, OO-ALC was the actual test facility for this project. The actuator workload generally constitutes from 5-15% of the total workload at the depot which was also the lead test facility for the HVOF landing gear project [3]. Although Air Force actuators are overhauled at OO-ALC, the cognizant authority is located at Tinker AFB. As a result, the component qualification testing was performed at Oklahoma City, generally by companies under contract to the Air Force.

Within the Navy, actuators are overhauled at all three NADEPs, Jacksonville, North Island and Cherry Point. Each depot is responsible for overhauling specific types of aircraft, so they would overhaul the actuators on those aircraft as well. Jacksonville and Cherry Point already each have two production HVOF systems in operation and therefore can implement the technology on actuator components once approvals have been obtained.

3.3 TEST FACILITY HISTORY/CHARACTERISTICS

OO-ALC, supported by Tinker AFB, was considered to be the lead test facility since the Air Force was performing the most work among the services to qualify HVOF thermal spray coatings on actuator components and, as indicated above, most Air Force actuators are overhauled at that repair facility.

OO-ALC is the largest employer in Utah, with more than 23,500 civilian, military, and contractors supporting an estimated 7.5 million production hours. The center has worldwide engineering, sustainment and logistics management and maintenance support responsibilities for some of the Air Force's most sophisticated weapon systems. It is the Air Force Center of Industrial and Technical Excellence (CITE) for low-observable aircraft structural composite materials and provides support for the B-2 Spirit multi-role bomber. Program management for two of the Air Force's fighter aircraft is performed at this center. Hundreds of F-16 Fighting Falcon and A-10 Thunderbolt jet aircraft annually receive depot maintenance, modification and repair on the base. The center performs depot maintenance on the C-130 Hercules and is responsible for program management of the KC-135 Stratotanker workload in partnership with the Boeing Aerospace Support Center in San Antonio, Texas. The center has responsibilities for Air Force-wide item management, depot level overhaul and repair for all types of landing gear, wheels, brakes, and hydraulic actuators, and is the logistics manager for all conventional air munitions, solid propellants and explosive devices used throughout the Air Force.

OO-ALC maintains several hard chrome plating tanks of differing sizes for reworking components such as pistons, cylinders, axle journals and attachment pins. In 2003, the depot applied hard chrome to more than 10,000 landing gear and actuator components and used more than 13,000 pounds of chromic acid. Additional operations support the hard chrome plating process, including stripping, cleaning, masking, grit blasting, oven baking and inspection. The entire hard chrome plating process is performance in accordance with MIL-STD-1501 supported by QQ-C-320.

OO-ALC currently has two full-production HVOF systems in operation and expects to install an additional three systems by early 2007. The depot has qualified and converted approximately 50 landing gear components from EHC to HVOF WC/Co or WC/CoCr.

3.4 PHYSICAL SET-UP AND OPERATION

OO-ALC has two TAFA JP-5000 HVOF thermal spray systems that are capable of production operation. Figure 3 shows the inside of one of the HVOF spray booths with the air handler in the background, the robot on which the spray gun in mounted directly in front, and the powder feeder at the left. Figure 4 shows the application of an HVOF coating onto a C-5 pitch cylinder

with air cooling jets and an infrared pyrometer located above the component for monitoring surface temperature during coating deposition.

Figure 3. Inside of HVOF Spray Booth at OO-ALC Showing Air Handler in Background and Robot on which HVOF Spray Gun is Mounted Directly in Front.

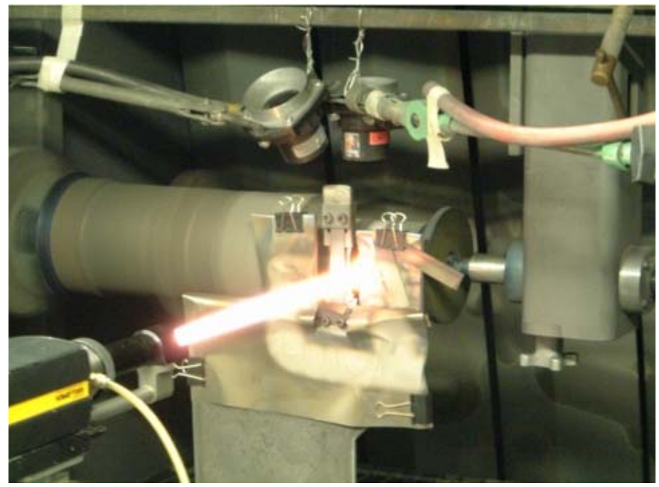

Figure 4. Application of HVOF Coating to C-5 Pitch Cylinder in OO-ALC Spray Booth.

3.5 BASE MATERIAL SELECTION AND COATING DEPOSITION

The stakeholders selected three alloys, 4340 steel, PH15-5 stainless steel and Ti-6Al-4V, as the base materials for evaluating the HVOF coatings compared to EHC plating. These alloys were viewed as being most representative of the alloys used in hydraulic actuators on which EHC is currently applied. The composition of the alloys is given in Table 2.

Table 2. Composition of Alloys Selected for Materials Testing.

Composition in Weight %												
Alloy	**Ni (+Co)**	**Cr**	**Fe**	**Mo**	**Nb+Ta**	**Ti**	**Al**	**C**	**Mn**	**Cu**	**Si**	**V**
4340	1.75	0.8	95.8	0.25	----	----	----	0.40	0.70	----	0.3	----
PH15-5	3.5-5.5	14.0-15.5	~ 75	-----	0.15-0.45	----	----	0.07	1.00	2.5-4.5	1.00	----
Ti-6Al-4V	----	----	0.13	----	----	~ 90	6.0	0.04	----	----		4.0

Table 3 provides the tensile strength values for each alloy which defines the type of heat treatment to which each alloy was subjected.

Table 3. Tensile Strength Values for Each Alloy.

Material	Tensile Strength
4340	180-200 ksi
PH15-5	155 ksi (condition H1025)
Ti-6A1-4V	130 ksi (annealed condition)

The stakeholders selected three HVOF thermal spray coatings to be compared to EHC plating for the materials tests. These were:

WC/10Co4Cr
Cr_3C_2/20(80Ni-20Cr)
Tribaloy 400 (nominal composition 57Co-28.5Mo-8.5Cr-3.0Ni-3.0Si)

In general, test specimens were fabricated and shot-peened in one facility and then transported to the facility performing the coating application. The surfaces of the test specimens onto which the coatings were to be applied were shot peened using cut wire (CW-14) to an intensity of 8-10A in accordance with AMS-2432 under computer control with 100% surface coverage. The Ti-6Al-4V specimens were cleaned with nitric acid immediately following shot peening.

At the coating facility, the surfaces of the test specimens onto which the coatings were to be applied were grit blasted not more than 2 hours prior to coating deposition. Surfaces to receive EHC plating were grit blasted with #13 glass bead in accordance with AMS-QQ-C-320. Surfaces to receive the HVOF coatings were grit blasted with 54-60 mesh aluminum oxide at 40-60 psi at a 90º angle of impingement in accordance with MIL-STD-1504. A uniform standoff distance of 4-6 inches was used. The Ti-6Al-4V was not grit blasted due to concerns about embedded grit creating stress risers that could affect mechanical properties such as fatigue. Instead, the Ti-6Al-4V was cleaned with acetone immediately prior to coating application.

The EHC coatings were deposited in accordance with MIL-STD-1501D (Class 2, Type II), supported by AMS-QQ-C-320. There was no interfacial layer between the specimen and EHC coating. No sealer was applied to the EHC.

The as-deposited thickness was at least 0.002” greater than the final required thickness. Subsequent to application, each specimen was baked at 375ºF for 23 hours to remove any hydrogen. Then the coating was ground to final dimension with an Ra surface finish of 12-16 microinches using low-stress grinding techniques in accordance with MIL-STD-866.

The HVOF coatings were applied to test specimens within 30 minutes after grit blasting. They were applied using a Sulzer Metco Diamondjet hybrid HVOF thermal spray gun in accordance with Boeing Specifications BAC 5851, Class 2, with the types as indicated in Table 4. Uniform deposition conditions were utilized for all specimens. Air cooling and/or built in pause times off the specimen as required were utilized to ensure the surface temperature did not exceed 375°F for all specimens. To ensure uniform internal stress in the coatings, initial depositions were made on Almen N strips, with the deposition parameters adjusted such that the Almen N values as indicated in Table 4 were obtained.

Table 4. HVOF Coating Deposition Specifications and Almen N Strip Values.

Coating	Spec.	Almen N Range
WC-10Co4Cr	BAC 5851, Class 2, Type XVII	4-12
Co-28 Mo-8 Cr-2 Si (Tribaloy T-400)	BAC 5851, Class 2, Type XV, optimized per HCAT specs	4-12
Cr_3C_2-20/Ni-Cr	BAC 5851, Class 2, Type XVI	4-12

Prior to application of the actual coating, the specimens were preheated using the HVOF gun to a temperature sufficient to remove all moisture. The substrate preheat temperature did not exceed 375°F. The temperature on the surface of the specimens was measured using a laser sighted infrared thermometer with adjustable emissivity (0.1 to 0.99) and response time of less than 1 second. The measurement was made one spot removed from the trailing edge of the plume path as it traversed the area being coated. To avoid oxidation, the Ti-6Al-4V specimens were not preheated.

Air cooling was used to ensure the specimen surface temperature did not exceed 375°F. The angle of incidence of the spray plume to the surface of the specimen was maintained at 90º, although for small cylindrical specimens such as fatigue bars, the plume width was greater than the diameter of the gage section, so the particles were impinging on the surface at variable angles.

The as-deposited thickness of the HVOF coatings was generally 0.003”-0.004” greater than the final required thickness. After deposition, the coatings were ground with a diamond abrasive wheel to 8-10 Ra (10-14 Ra for T-400) using low-stress grinding techniques.

Prior to each HVOF run, the HVOF coatings were deposited onto test coupons and characterized to ensure they were meeting the required characteristics and properties. Cross-section metallography was used to measure the porosity and amount of oxides in the coatings.

The Vickers microhardness of each coating was measured using an indenter load of 100 grams. Multiple measurements were taken across the surface and an average microhardness was computed. Adhesion bond strength measurements were taken in accordance with ASTM C-633. The strength of the epoxy was determined to be between 10,500 and 11,500 psi. For all HVOF coating adhesion measurements, the failure occurred in the epoxy, indicating that the coating bond strength exceeded 10,500 psi.

As indicated above, Almen N strips were used as a quality control method for determining the internal stress in the coatings. In all cases the internal stress was compressive. The specific methodology for spraying the Almen N strips was provided in the Materials JTP [6]. For different thickness coatings, Almen N numbers were normalized to a thickness of 0.005”.

Table 5 provides average values for oxide content, porosity, microhardness and Almen N values for each of the three HVOF coatings. By way of comparison, the Vickers microhardness for the EHC used in these studies ranged from 900-930 HV.

Table 5. Results of Measurements of Oxide Content, Porosity, Microhardness and Almen N Strip Values.

Parameter	Wc/Cocr	Cr_3c_2/Nicr	T-400
Oxide Content	< 1% @ 200X	< 1% @ 200X	< 1% @ 200X
Porosity	< 1% @ 400X	1.0 – 1.5% @ 400X	< 1% @ 400X
Microhardness	1150 HV	1115 HV	650 HV
Almen N	10.5	5.7	9.3

3.6 ANALYTICAL METHODS

The materials test methods and procedures were described in detail in the Materials JTP [6] and are only summarized here.

Fatigue

The purpose of fatigue testing was to evaluate the effect of the coating on the fatigue of the underlying material, in particular comparing it with the fatigue debit induced by hard chrome plate. In addition, coatings must maintain their integrity under expected service conditions (i.e. not delaminate during testing at stresses seen in service, although delamination may occur on failure or at stresses in excess of service stresses).

Previous data has shown that HVOF coatings crack when their strain-to-failure is exceeded (typically at about 0.7% strain). Coatings tend to spall at a somewhat higher stress. Since actuator alloys are typically heat treated to have lower ultimate stress than landing gear alloys, yet have essentially the same elastic modulus, high strain effects such as coating integrity and spalling should be less significant for actuators. Nevertheless, for safety and completeness, spalling checks were incorporated into the actuator fatigue JTP.

All fatigue specimens were fabricated from round bar taken from the same heat treating lot for each material. Specimens were in the form of a standard hourglass bar, 0.25-inch gage diameter. Specimens were shot peened to AMS 2432 under computer control to 100% surface coverage using 8-10A, S110, wrought steel shot.

Coating deposition was carried out as described in the previous section. Grit blasting was performed prior to HVOF spraying on all except the Ti-6Al-4V substrates. Spraying was carried out over the gage length, and coatings were ground to a final thickness of 0.004" and a finish of 8-10 microinches Ra.

Load-controlled constant amplitude axial fatigue testing was conducted in accordance with ASTM E466-96 under the following conditions:

- Baselines – standard S-N curves for uncoated and hard chrome plated specimens
- Data at 10 points for all coated specimens. Loads were spread between the maximum used for the uncoated curves and the runout load.
- R ratio: R = -1
- Environment: Laboratory air at ambient temperature

Stress levels: Uncoated specimens were first run at the following loads to determine the stress-strain curve for each substrate:

- High load – approximately 85% of yield strength
- Low load – A load at which the uncoated specimen fatigue life was approximately 106 cycles (runout defined as 107 cycles).
- Intermediate loads –Loads spread between the high and low load, usually with one point per load, but no more than two points per load.

During testing specimen surfaces were examined visually at approximately 25%, 50% and 75% of expected life, and finally after failure. Notations were made in the test data when cracking or spalling was observed. The surfaces were photographed if there was evidence of spalling.

<u>Corrosion</u>

Flat panels, 3” x 4” x ¼”-thick, were fabricated from each of the alloys indicated in Section 3.5. One face of each panel was ground to a surface finish of 32-64 microinches Ra. Then each ground face was shot peened, grit blasted, and coated with either EHC or an HVOF coating as described in Section 3.5. Only WC/CoCr and T-400 HVOF coatings were applied to the panels.

For EHC deposition, a l”-wide area at the bottom of each panel was masked such that the coated area was 3” x 3”, with coating applied to both faces and the edges. HVOF coatings were applied on the ground 3” x 4” face only.

As-deposited coating thicknesses were either 0.007” or 0.013”. Subsequent to deposition, each coating was ground to a final thickness of either 0.004” (± 0.0005”) or 0.010” (± 0.0005”), with an Ra surface finish of 12-16 microinches for EHC, 10-14 microinches for the HVOF T400, and 8-10 microinches for the WC/CoCr.

Just prior to initiating the ASTM B117 salt fog corrosion test, the reverse side and edges of each panel were coated with an inert epoxy resin to ensure that only the one coated face was exposed to the corrosive media. On the EHC-coated panels, the 1” x 3” non-coated area on the front face was also coated with the epoxy. Note that the epoxy extended beyond the edges onto the coated front face for about 0.25” to ensure that there were no edge effects.

In addition to the flat panels, one-inch-diameter, six-inch-long rods were fabricated from each of the alloys indicated in Section 3.5. The curved surface on each rod was ground to a surface finish of 32-64 microinches Ra. Then the curved surface was shot peened, grit blasted, and coated with either EHC or an HVOF coating as described in Section 3.5. Figure 5 is a schematic of the rod, indicating the areas that were shot-peened, grit blasted and coated. As-deposited

coating thicknesses were either 0.007” or 0.013”. Subsequent to deposition, each coating was ground to a final thickness of either 0.004”or 0.010” (± 0.0005”), with an Ra surface finish of 12-16 microinches for EHC, 10-14 microinches for the HVOF T400, and 8-10 microinches for the WC/CoCr and Cr_3C_2/NiCr. There were two 0.013”-thick EHC coatings on 4340 that were ground excessively to final thicknesses of 0.007” (± 0.005”). Subsequent to grinding, three of the WC/CoCr coatings on 4340 were superfinished, with an Ra surface finish of 2-4 microinches.

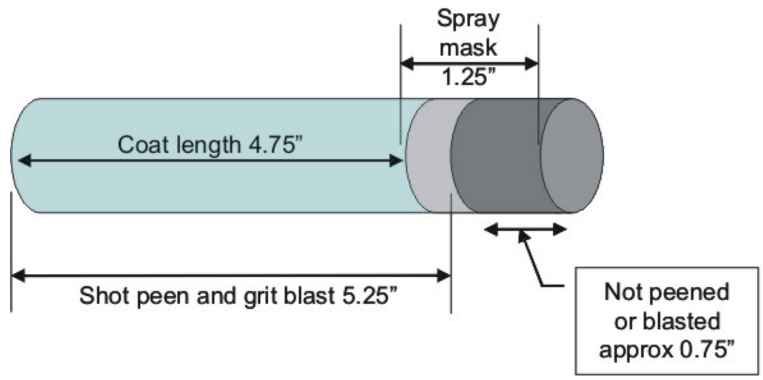

Figure 5. Schematic of the Corrosion Rods, Indicating the Areas that were Shot-Peened, Grit-Blasted, and Coated.

Just prior to initiating the corrosion test, the flat ends and a 1.5” length at the bottom of each rod were coated with an inert epoxy resin to ensure that only the coated areas were exposed to the corrosive media.

Fluid Immersion

In order to utilize HVOF thermal spray coatings instead of EHC plating on hydraulic actuator components, stakeholders must consider coating compatibility with all fluids that come into contact with the coating during manufacture, service and maintenance. These include lubricating oils, hydraulic fluids, solvents, and cleaning compounds, as well as greases used for preservation and operation, and deicing fluids used in the airfield. The coating should be inert to the working fluids or greases, and not crack, flake, pit, soften or separate under any expected conditions of fluid or grease exposure. To adequately assess the performance of coatings under simulated real-life conditions, the fluid or grease immersion temperature should be similar to the actual usage temperature and the test specimens should be either fully submerged or partially submerged in the fluid, reflecting their usual service or maintenance conditions. In developing the JTP, the stakeholders did not require immersion testing of EHC coatings since there was already ample operating experience that indicated that EHC was not affected by the fluids tested.

For the fluid immersion tests, 1”-diameter 4340 steel rod was cut into disks 0.05” thick, with both faces of each disk ground to a surface finish of 32-64 microinches Ra. Because the immersion tests were only to assess the behavior of the coatings under exposure, the substrates were not shot peened. Both faces of each disk were grit blasted and then coated with HVOF WC/CoCr, Cr_3C_2/NiCr, or T-400 using the parameters as specified in Section 3.5. The nominal as-deposited coating thicknesses were 0.0055” for all coatings. The coatings were not ground prior to the fluid immersion tests.

The following fluids were specified in the JTP for immersion testing:

1. MIL-PRF-83282 hydraulic fluid
2. Skydrol AS1241 Type 4 hydraulic fluid
3. Non-destructive inspection (NDI) fluorescent penetrant dye, ARDROX 985-P14
4. Propylene glycol, commonly used for de-icing procedures
5. Nital etchant, a 4% by volume mixture of nitric acid in alcohol
6. Ammonium persulfate etchant, 10% by weight mixture with water
7. MIL-C-87937 cleaner, d-limonene based, mixed one part cleaner to two parts water
8. Oakite 90 cleaner, mixed 8.5 ounces per gallon of water
9. Chlorine bleach, sodium hypochlorite, common household bleach mixed 60% with water to yield a solution of approximately 3% by volume NaOCl
10. Cee-Bee J-84A, a high pH, heavy duty degreaser, mixed 8.5 ounces per gallon of water
11. Turco Vitro-Klene heavy duty soak cleaner, mixed 8.5 ounces per gallon of water
12. JP-5 jet fuel

Since the edges of the disks were not coated, the edge around each specimen was coated with Dow Epoxy Resin 324 hardened with triethylenetetramine such that it extended slightly onto the coating on each face, with the epoxy allowed to cure overnight at room temperature. Then photographs were taken at the approximate center of each specimen at 25X optical magnification.

Any chemical attack on the HVOF coatings caused by fluid immersion would likely be manifested as changes in the surface roughness. Therefore, the surface roughness near the center of each specimen was measured with a Mahr Perthometer S2 digital profilometer. Then each specimen was weighed using a Mettler AE-200-S mass balance with 0.1 mg readability and reproducibility.

Two specimens of each of the three coating groups were tested in each fluid. With 12 fluids, this resulted in a total of 72 specimens being evaluated.

After the prescribed immersion times, each specimen was removed from its jar and excess fluid was wiped off with a paper towel. Then each specimen was thoroughly rinsed with isopropanol and dried with a jet of clean, dry air. The ARDROX penetrant was rinsed with water rather than isopropanol. Water rinsing was used to remain consistent with NDI procedures. After cleaning, each specimen was allowed to dry in open air for one to three minutes and then weighed using the procedure for the pre-test weighing. Further, each specimen was reweighed after drying in open air for approximately 48 hours. Finally, each specimen was photographed at 25X, similar to the pre-test photographs and then the surface roughness measurements were repeated.

<u>Environmental Embrittlement</u>

Previous work had already shown that deposition of HVOF thermal spray coatings did not cause hydrogen embrittlement of different types of materials, including high-strength steels [3].

Therefore, the only important issue was whether, for the types of materials used in actuators, use of an HVOF coating accelerates environmental embrittlement which usually occurs as a result of corrosion of a coating or substrate that can produce hydrogen.

Special ASTM F519 Type 1a.2 hydrogen embrittlement bars were fabricated from the materials in the heat-treat condition as indicated in Section 3.5. In previous HVOF spraying of these types of specimens, the overspray material, which would normally bounce back off the surface, tended to become trapped in the notch, producing a thicker and more porous coating. In order to minimize this entrapment for these specimens, a strong air stream was directed into the notch and the HVOF coatings were applied with the gun at an angle of 30° to the normal. During coating application the specimens were rotated while the gun was traversed, angling the gun at +30° from the normal when traveling in one direction and -30° from the normal when traveling in the other direction. During coating application, air cooling was used to ensure the surface of the specimen did not exceed 375ºF. On all bars, a cut was made through the coating in the notch with a shaped diamond-cutting wheel to just expose the substrate all around the circumference within the notch. The blade was driven into the notch to cut just into the underlying material and then the blade was rotated around the specimen. Each specimen was visually examined at 10x to ensure complete coating removal in the scribed area before removing the sample from the machining holder.

Functional Rod/Seal Testing

Project stakeholders determined that a test rig located at NAVAIR Patuxent River would be ideal as a screening tool for evaluating the performance of various HVOF thermal spray coatings with different surface finishes against different types of seal materials. The performance of HVOF-coated rods would also be directly compared against the baseline performance of EHC-plated rods. The intent of the testing performed in this project was to collect data on not only the performance of HVOF-coated rods compared to EHC-plated rods, but also to determine the optimum surface finishes on the HVOF-coated rods to minimize seal wear.

Two phases of functional rod/seal tests were performed. The objective of Phase I was to validate HVOF WC/CoCr as an acceptable replacement for EHC by conducting unloaded cyclic testing of four different seal configurations. The objective of Phase II was to conduct unloaded cyclic testing of one seal configuration against WC/CoCr with different surface finishes as well as one additional HVOF coating, WC/Cr_3C_2/Ni (73/20/7). Although T-400 coatings were evaluated in the materials tests, most stakeholders believed that the WC-based coatings would be the ones most likely to be implemented on actuator pistons. For that reason and because of funding limitations, the T-400 coatings were not evaluated in the rod/seal tests.

The test rig consisted of a master hydraulic piston that drives four test rods, each of which passes through two blocks. The portion of the apparatus consisting of the blocks and test rods is mounted inside an environmental chamber capable of maintaining a temperature between -65° and +300°F. The master piston passes through a sealed port on the environmental chamber. The hydraulic power supply is located outside the chamber for increased reliability of the test hardware. A detailed description of the test rig is provided in the final report [7].

MIL-PRF-83282 hydraulic fluid that was filtered with 5 micron elements and maintained to a Navy Class 4 or better contamination level was used for all tests. The drive piston operates at 3000 psi and static pressure acts on the seals in the block end cap that have ports on the top. A total of eight block end caps each have four seal grooves in accordance with MIL-G-5514 for a one O-ring and two backup groove width. Pressure was applied to each block from the top center and collection of leakage was measured in two locations per block. Leakage was collected in beakers set up between the test (primary position) and dummy (secondary position) seals such that only the test seal was evaluated and the dummy seal acted as a barrier to direct leakage to the collection beakers. There was no external loading provided by this test fixture.

For both phases the test rods were fabricated from PH13-8Mo stainless steel and were 16 inches in length and nominally 1 inch in diameter. For Phase I testing, the rods were grit blasted and HVOF WC/CoCr coatings were applied to rods numbered 1 through 3 as described in Section 3.5 and EHC was applied to rod number 4 as described in Section 3.5. The coating on Rod #1 was ground using a 320 grit diamond wheel, the coating on Rod #2 was ground using a 120 grit diamond wheel and then superfinished using the oscillating stone method, the coating on Rod #3 was ground using a 220 grit diamond wheel and then superfinished using the oscillating stone method, and Rod #4 was ground using a 60 grit alumina wheel.

Shamban, Green-Tweed and CoorsTek each provided four different seal configurations. From the received seals, the following seals in Table 6 were randomly selected for testing. The supplier of the spring energized PTFE configuration installed their seals in the blocks because the installation technique required specific skills to prevent the seals from becoming easily damaged. NAVAIR Patuxent River engineers installed the remaining seal configurations in the block cap glands and rods in the block fixture.

Table 6. Phase I Seal Configurations.

Seal Configuration	Supplier	Part Number
#1 MIL-P-83461 O-ring and PTFE Cap strip	Busak+Shamban	O-ring (M83461/1-214) Double Delta (S32851-214-19N) Backup Ring (S11248-214-10)
#2 MIL-P-83461 O-ring and 2 backup rings	Greene Tweed Busak+Shamban	O-ring (A921499-00161) Backup Ring (2114-214-079) O-ring (M83461/1-214) Backup Ring (M8791/1-214)
#3 Fluorosilicon O-ring PTFE cap strip	CoorsTek	O-ring (TF2-214-813) Tetralon 902 Tetracap Seal (TF238M214-902N)
#4 Spring energized PTFE seal	CoorsTek	Metaplast Seal (TF888L214-902C) Backup Ring (TF91-214-901)

For Phase II testing, three rods were coated with HVOF WC/CoCr and a fourth rod was coated with WC/Cr_3C_2/Ni. The deposition parameters for the latter coating were essentially the same as for the WC/CoCr. This testing was intended to evaluate eight different processed rod halves on the four rods with only one seal configuration. The purpose was to evaluate the performance of ground versus superfinished coatings and whether there was a difference between the

performance of coatings superfinished using the oscillating stone methods and those superfinished using the tape method. One seal configuration, MIL-P-83461 O-ring and dual backup rings, provided by Greene-Tweed, was used in all blocks for the Phase II test. NAVAIR Patuxent River engineers installed the seals in the block cap glands and rods in the block fixtures.

A specific temperature and cycling spectrum was established for the tests which were run for 8 hours per day for 16 days to achieve a total of 1,040,000 cycles. The test specimens and fixture were maintained at 0°F between each day of testing to evaluate static leakage at start-up. There was a static pressure of 3000 psi applied to both ends of each test block. The tests were run for a specific number of cycles at 160º, 200º, 225º, 250º, 275º and finally -40ºF.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

The performance criteria for all of the materials testing were delineated in Section 3.1. For all materials testing, the essential criterion was that the performance of specimens coated with HVOF thermal spray coatings was equivalent or superior to the performance of identical specimens coated with EHC. Acceptance criteria for rig tests conducted on components were that the HVOF coatings did not show any evidence of delamination, cracking or extensive wear and that the performance was equivalent or superior to what would be expected for EHC in the same rig test.

4.2 PERFORMANCE DATA

All of the performance data for the materials and functional rod/seal testing are presented in detail in the Final Report [7]. Only selective data and summaries are provided here.

<u>Materials Testing – Fatigue</u>

The fatigue testing examined the performance of specimens fabricated from the alloys listed in Table 2 and coated with EHC compared to specimens coated with the HVOF thermal spray coatings listed in Table 4. Fatigue performance was assessed through plots of cycles-to-failure as a function of the maximum stress (S/N plot) to which the specimens were subjected. The following represents a summary of the results.

4340 steel substrates: Figure 6 shows the S/N plot for uncoated baseline and the EHC-coated and WC/CoCr-coated specimens. The solid red line represents a least-squares-fit to the EHC data. Within statistical uncertainty, the fatigue performance of the three types of specimens was considered to be equivalent. Spalling was noted on one WC/CoCr-coated specimen which occurred essentially at runout. The performance of the Cr_3C_2/NiCr-coated specimens was essentially equivalent to those coated with EHC. Cracking of the HVOF coating was observed at runout at the lowest load, while spalling occurred in the gage section at the highest load. The fatigue performance of the specimens coated with T-400 was superior to those coated with EHC. No cracking or spalling of the coatings was observed.

PH15-5 stainless steel substrates: Figure 7 shows the S/N plot for uncoated baseline and the EHC-coated and WC/CoCr-coated specimens. The fatigue performance for the HVOF-coated specimens was slightly above that for those coated with EHC. Cracking of the HVOF coating was observed above 1 million cycles, but no spalling was observed. The performance of the Cr_3C_2/NiCr-coated specimens was essentially equivalent to those coated with EHC. Cracking of the HVOF coating was observed at approximately 6 million cycles. The fatigue performance of the specimens coated with T-400 was significantly superior to those coated with EHC. No cracking or spalling was observed.

Ti-6Al-4V substrates: There were many spalling failures of both EHC and HVOF coatings due to inadequate surface preparation (discussed in the next section). The relative fatigue performance of coated specimens was assessed only for those specimens for which spalling was

not observed. The fatigue performance of the WC/CoCr-coated specimens was equivalent to that of the EHC-coated specimens below 1 million cycles, but then was inferior above 1 million cycles. The fatigue performance of the Cr_3C_2/NiCr-coated specimens was inferior to that of the EHC-coated specimens. The fatigue performance of the specimens coated with T-400 was essentially equivalent to that of the EHC-coated specimens.

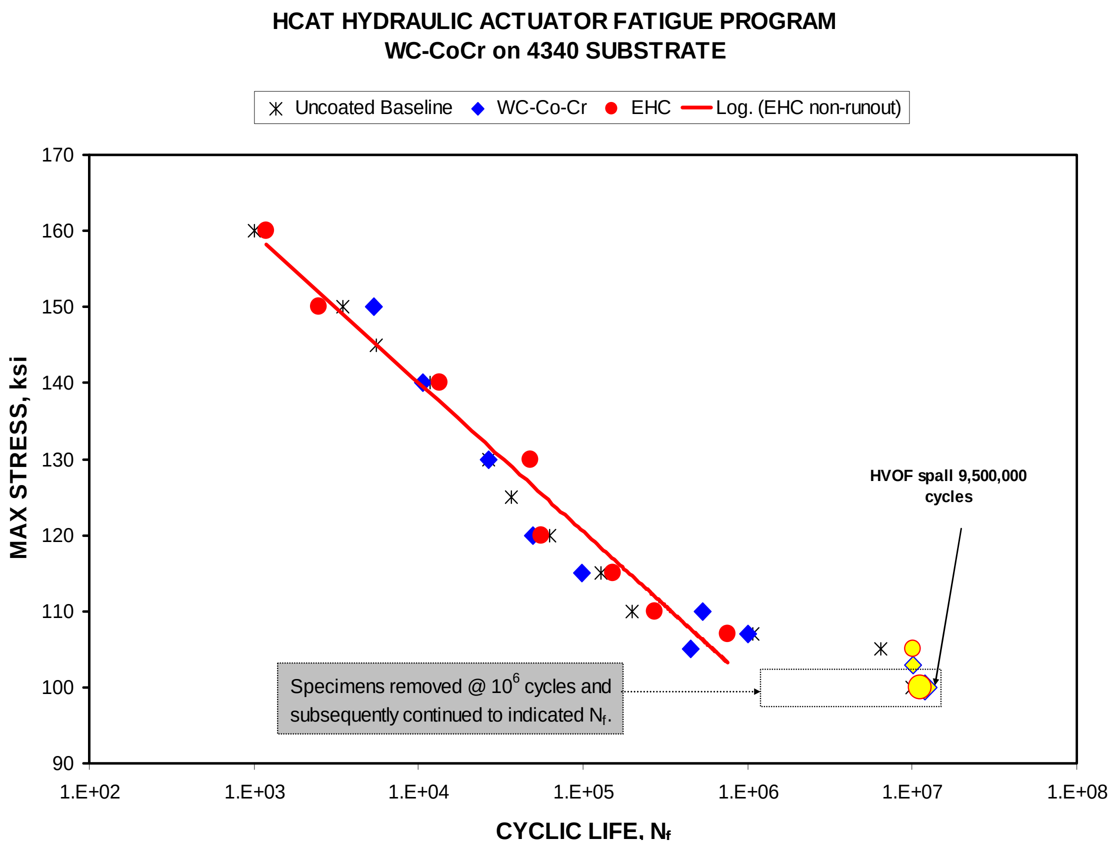

Figure 6. Fatigue Data for 4340 Specimens Uncoated and Coated with EHC and HVOF WC/CoCr.

<u>Materials Testing – Corrosion</u>

The corrosion specimens were placed into a standard salt fog corrosion chamber in holders that maintained them at an angle of 25º from the vertical. They were then subjected to a constant 5% NaCl salt fog environment at 95ºF in accordance with ASTM B117. During the testing, the specimens were removed from the chamber, photographed, and evaluated at 0, 125, 250, 375, 500, 625, 750, 875, and 1000 hours of exposure. Evaluations were conducted in accordance with ASTM B537. This specification assigns ratings of 0 to 10 (10 being best, 0 being worst) for two aspects of observed coating performance. "Protection" is determined by how well the coating protects the substrate from corrosion. "Appearance" incorporates the protection aspect but also accounts for other visual aspects of corrosion performance (staining, dripping, etc.) that might be considered detrimental but not a protection defect.

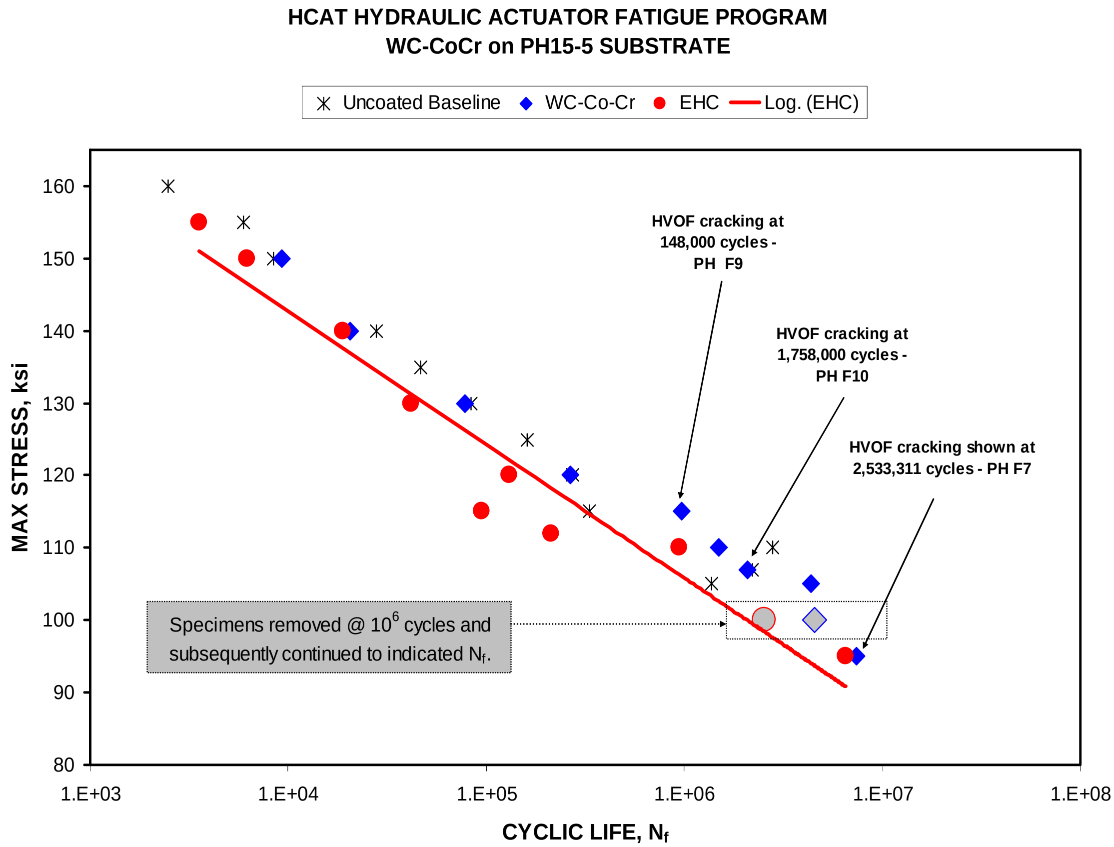

Figure 7. Fatigue Data for PH15-5 Specimens Uncoated and Coated with EHC and HVOF WC/CoCr.

Figure 8 presents the appearance ratings and coating thicknesses for the rods grouped by coating. The corrosion performance of the EHC-coated panels for all three substrate materials was superior to that of the three HVOF coatings, with an average rating of 10 on PH15-5, 9.7 on 4340 and 8.8 on Ti-6Al-4V. The performance of the HVOF Cr_3C_2/NiCr coatings was only slightly less than for the EHC, with average ratings of 8.8 on Ti-6Al-4V, 8.0 on 4340 and 6.8 on PH15-5. The performance of the WC/CoCr coatings was almost comparable to the Cr_3C_2/NiCr, with average ratings of 7.0 on PH15-5, 6.7 on Ti-6Al-4V and 5.4 on 4340. The corrosion performance of the T-400 coatings on the rods was inferior to the other coatings, with average ratings of 6.0 on PH15-5, 6.5 on Ti-6Al-4V and 3.5 on 4340.

The corrosion performance of the EHC-coated panels for all three substrate materials was superior to that of the two HVOF coatings. The average rating for the EHC-coated PH15-5 panels was 9.5, followed by the EHC-coated Ti-6Al-4V with an average rating of 7.1 and the EHC-coated 4340 with an average rating of 7.0. The performance of the T-400 coatings on all three substrates was almost comparable to that of the EHC coatings, with an average rating of 7.8 on Ti-6Al-4V, 6.8 on PH15-5 and 6.5 on 4340. The WC/CoCr coatings appeared to provide somewhat less protection, with an average 5.0 rating on PH15-5, 3.6 on Ti-6Al-4V and 2.8 on 4340. In terms of correlation with coating thickness, it was apparent that for the WC/CoCr coatings on 4340 and Ti-6Al-4V, the 0.010”-thick coatings provided substantially better corrosion protection than the 0.004”-thick coatings. However, for all other coating/substrate

combinations, there appeared to be no significant correlation between coating thickness and corrosion performance.

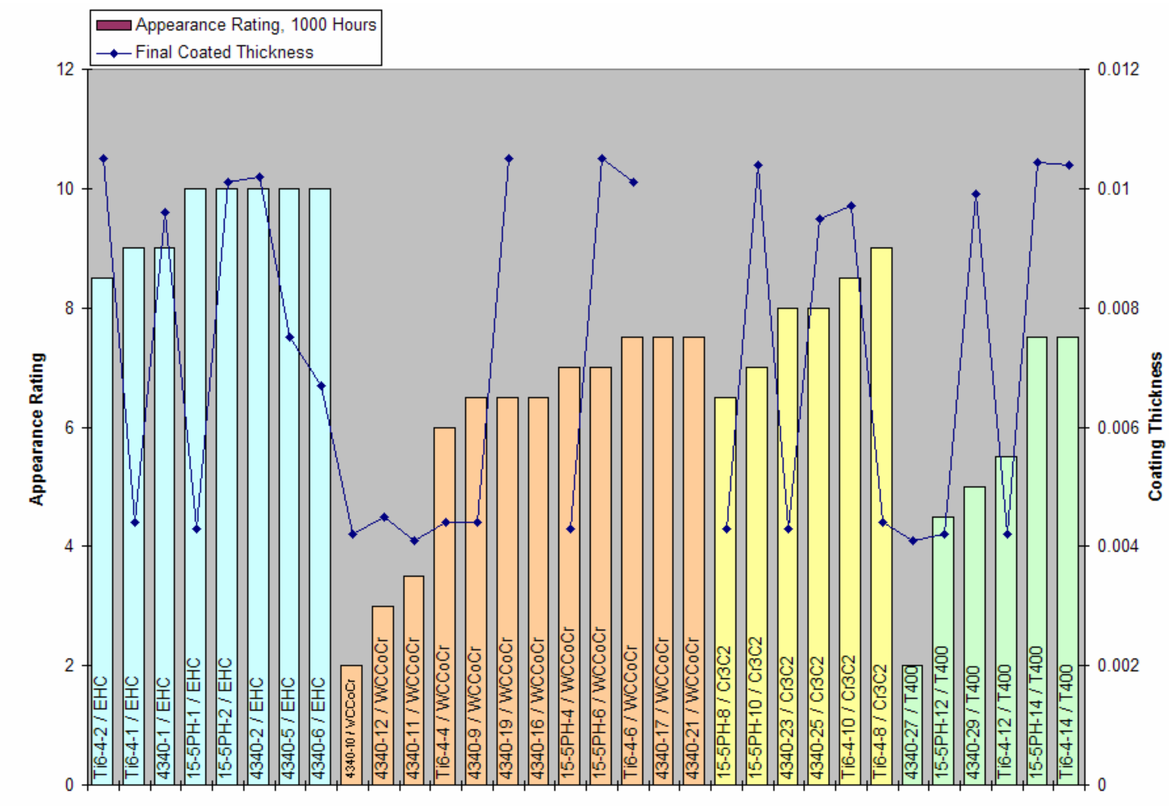

Figure 8. Appearance Ratings and Coating Thicknesses for EHC- and HVOF-Coated Rods, Grouped by Coating Material, and Shown from Worst to Best Corrosion Performance within Each Group.

Materials Testing – Fluid Immersion

In terms of weight loss and surface profilometry, with the exception of the sodium hypochlorite bleach , there was essentially no effect of the various fluids on the three HVOF coatings. There was a very small amount of weight loss associated with exposure of the T-400 coatings to the high pH, heavy-duty cleaners and the ammonium persulfate etchant. There was no effect on the surface roughness or visual appearance. There was a significant amount of mass loss to the two cobalt-containing coatings, WC/CoCr and T-400, due to exposure to the bleach. The visual appearance of the coatings also changed, with obvious coating degradation.

Materials Testing – Environmental Embrittlement

For each coating/substrate combination, three specimens were immersed in deionized (DI) water and three were immersed in a 5% NaCl solution and then subjected to a sustained tensile load of 45% of the notch fracture strength. The test requirements were that the sustained tensile load was to be maintained for a period of 200 hours or specimen fracture, whichever occurred first, in accordance with ASTM F519. If a specimen fractured, then the time to failure was to be recorded and the fracture surface photographed.

The results of these tests were that none of the specimens fractured prior to 200 hours.

Functional Rod/Seal Testing

For Phase I testing, Rod #1 contained a WC/CoCr coating ground using 320 grit diamond to a target roughness of 4-6 microinches Ra, Rod #2 contained a WC/CoCr coating ground to a nominal roughness of 20-22 microinches Ra using 120 grit diamond and then superfinished to a target roughness of 2 microinches Ra, Rod #3 contained a WC/CoCr coating ground to a nominal roughness of 8-10 microinches Ra using 220 grit diamond and then superfinished to a target roughness of 2 microinches Ra, and Rod #4 contained an EHC coating ground to a target roughness of 12-15 microinches Ra using 60 grit aluminum oxide. Table 7 lists the actual surface roughness values taken before and after the rod/seal tests.

Table 7. Initial and Final Surface Roughness Values for HVOF and EHC Coatings in Phase I Tests.

Rod Number	Coating	Initial Roughness	Final Roughness
1	WC/CoCr	6.5 microinches	3.5 microinches
2	WC/CoCr	2.3 microinches	2.2 microinches
3	WC/CoCr	1.5 microinches	1.4 microinches
4	EHC	12.3 microinches	4.0 microinches

It can be seen that for both as-ground rods the test resulted in a significant decrease in roughness which indicates that the sliding action of the coatings against the seals wore down the peaks in the surface profile. On the other hand, there was no change to the surface roughness during the test for Rods #2 and #3. This indicated that superfinishing protected the surface of the rods from wear.

Leakage of fluid was collected throughout the test period to determine the total leakage accumulated for each configuration, the leakage per temperature profile and calculated trend rate of leakage. Figure 9 presents a summary of the total leakage and leakage rate at the end of the test for each configuration.

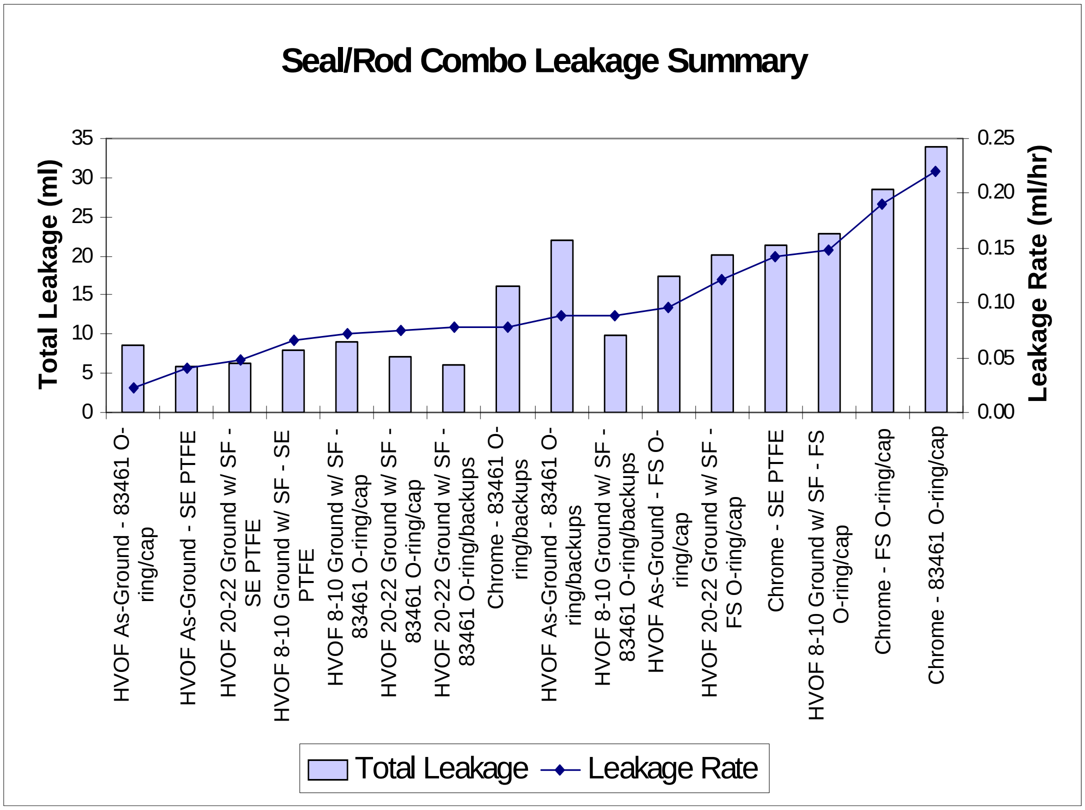

Figure 9. Summary of the Total Fluid Leakage and Final Leakage Rates for the Various Rod/Seal Configurations in Phase I Testing.

For Phase II testing, Table 8 provides the test gland identification, the type of coating, the final surface finish, the finish process, the cumulative fluid leakage from that gland and provides a relative ranking based on leakage. Note that Rp is the maximum peak height, Rz is the 10-point average of the highest peaks plus lowest valleys, Rsk is the skewness and Tp is the bearing ratio at a depth of 8 microinches.

Table 8. Ranking of the Finished Surfaces Based on Cumulative Fluid Leakage for Phase II Tests.

Rod Half	Test Gland	Material Coating	Final Surface Finish (Ra, Rp, Rz, Rsk, Tp)	Finish Process	Cumulative Leakage	Ranking
8b	BE2-C	WC/CoCr (86/10/4)	1,8, 7.1, 17.8, -2.2, 86%	Stone, Superfinish	27.0	Best
11a	FE4-B	WC-CR_3C_2-Ni (73/20/7)	2.9, 8.3, 37.8, -3.7, 84%	Film, Superfinish	29.4	Best
9a	FE3-B	WC/CoCr (86/10/4)	1.4, 4.4, 24.3, -5.8, 87%	Film, Superfinish	30.2	Best
8a	FE2-B	WC/CoCr (86/10/4)	2.4, 7.4, 37.2, -5.4, 85%	Film, Superfinish	32.8	Best
8b	BE2-D	WC/CoCr (86/10/4)	1.8, 7.1., 17.8, -2.2, 86%	Stone, Superfinish	35.6	Medium
9b	BE3-D	WC/CoCr (86/10/4)	2.1, 6.3, 24.8, -3.1, 85%	Stone, Superfinish	38.8	Medium
6b	BE1-D	WC/CoCr (86/10/4)	3.5, 10.6, 26.5, -0.6, 88%	Fine Stone, As-Ground	40.6	Medium
8a	FE2-A	WC/CoCr (86/10/4)	2.4, 7.4, 37.2, -5.4, 85%	Film, Superfinish	43.0	Medium
11a	FE4-A	WC-CR_3C_2-Ni (73/20/7)	2.9, 8.3, 37.8, -3.7, 84%	Film, Superfinish	46.0	Medium
9b	BE3-C	WC/CoCr (86/10/4)	2.1, 6.3, 24.8, -3.1, 85%	Stone, Superfinish	48.2	Medium
6b	BE1-C	WC/CoCr (86/10/4)	3.5, 10.6, 26.5, -0.6, 88%	Fine Stone, As-Ground	51.6	Medium
9a	FE3-A	WC/CoCr (86/10/4)	1.4, 4.4, 24.3, -5.8, 87%	Film, Superfinish	53.6	Medium
11b	BE4-D	WC-CR_3C_2-Ni (73/20/7)	2.8, 5.5, 54.2, -6.7, 81%	Stone, Superfinish	65.0	Worst
11b	BE4-C	WC-CR_3C_2-Ni (73/20/7)	2.8, 5.5, 54.2, -6.7, 81%	Stone, Superfinish	67.4	Worst
6a	FE1-B	WC/CoCr (86/10/4)	11.1, 42.7, 92.2, -1.1, 87%	Coarse Stone, As-Ground	71.4	Worst

Component Tests

The Oklahoma City Air Logistics Center (OC-ALC), in conjunction with the Air Force System Program Directors and the actuator/airframe OEMs, developed a plan for qualification and insertion of HVOF thermal spray coatings to replace EHC plating on most of the actuators used on Air Force aircraft.

Initially, they worked to identify and catalog chrome plated parts embedded in hydraulic actuators managed by OC-ALC in order to determine the best approach to implementing alternatives to EHC plating during actuator manufacture and overhaul which is performed at Ogden ALC (OO-ALC). Those actuators managed by OC-ALC and overhauled at OO-ALC were the principal focus so that the chrome plating requirement at the actuator depot facility could be reduced, if possible.

The effort was divided up by weapon system, based on the volume of actuators overhauled at OO-ALC and the anticipated future life of the weapon system. They examined in detail nine weapon systems (B-1, C-135, A-10, C-130, C-141, T-38, F-15, E-3, B-52). When this effort was initiated in 2001, there were approximately 125 Technical Orders (TOs) covering actuators overhauled at OO-ALC. Follow-on activities included similar reviews of TOs and drawings for field repaired actuators and for other hydraulic components managed by OC-ALC. It was expected that their number would be as large or larger than those covering depot overhauled actuators.

OC-ALC established a contract with ARINC to review TOs and drawings for flight control and utility actuators, and to construct and populate a searchable database with which one could view component identities, similarities and differences.

The intention was to select several actuators from these weapon systems and perform delta-qualification type testing on them as deemed necessary by the stakeholders. Actuator testing would be tailored for the specific actuator, would be based on original qualification requirements, and would address issues such as fatigue, endurance, and corrosion, as required. Completed material and component testing would be considered during determination of test requirements. The intent was to select actuators that impose the heaviest chrome plating load on OO-ALC, that represent a diversity of materials and seal designs, and that have sufficient commonality to other similar designs within and across weapon systems that could allow for qualification by similarity.

An overall four-phase program was established as follows:

- Phase 1: Tech Order and drawing review, database development and test requirement development
- Phase 2: Delta qualification and service testing
- Phase 3: Data evaluation
- Phase 4: Implementation

ARINC completed Phase 1 in late 2003. They reviewed 124 Air Force Technical Orders, 729 engineering drawings, and identified 276 EHC-plated components and 195 potentially EHC-plated components. For delta qualification and service testing, all actuators containing EHC-plated components were broken down into three categories:

- Flight control actuators (87 distinct part numbers)
- Utility actuators (73 distinct part number)
- Snubbers/Others (12 distinct part numbers)

The following flight control actuators were identified for delta qualification:

- C-130 Rudder Booster Actuator
- B-1 Horizontal Stabilizer
- B-1 Pitch/Roll SCAS
- A-10 Aileron

- F-15 Pitch/Roll Channel Assembly (PRCA)
- T-38 Aileron Actuator

The following utility actuators were identified for delta qualification:

- C-130 Ramp Actuator
- C/KC-135 Main Landing Gear Actuator
- C/KC-135 Main Landing Gear Door Actuator

The following snubbers and other actuators were identified for delta qualification:

- C-135 Aileron Control Surface Snubber
- KC-135 Ruddevator

A two-year service test period was planned for a number of actuators. These included:

- C/KC-135 Snubbers, Main Landing Gear Actuator, Main Landing Gear Door Actuator and Ruddevator
- C-130 Rudder, Elevator, Aileron, Ramp, and Aft Cargo Door Actuators
- A-10 Aileron, Rudder, and Elevator Actuators

Much of the testing is still ongoing as of the date of this report. The following summarizes the results obtained to date.

C130 Rudder Booster Actuator: HVOF WC/CoCr was applied to the piston rod and trunnion OD and ID, and T-400 to the piston heads. Three WC/CoCr-coated rods completed a 1-million-cycle test for which the temperature was varied between -65ºF and +160ºF. Three types of seals were used and they all passed the test with minimal fluid leakage. On the other hand, a piston rod with the standard EHC coating failed after 415,000 cycles.

B-1 Horizontal Stabilizer: Both the forward and aft pistons were coated with HVOF WC/CoCr. Qualification testing was performed by Boeing and included an endurance test of 750,000 cycles, representing approximately 50% of the aircraft life. The test was successfully completed with no unallowable fluid leakage and no wear on the coatings.

B-1 Pitch/Roll SCAS: HVOF WC/CoCr coatings were applied to the piston rods and head. Qualification testing is currently in progress at Boeing.

A-10 Aileron: HVOF WC/CoCr coatings were applied to the piston rods and heads. The qualification testing was performed by Parker Hannifin which consisted of a 1,875,200 cycle endurance test and a temperature cycling test in a range of -40ºF to 275°F. Seals used during the test were Coorstek Metaplast. Salt fog tests were also performed on WC/CoCr-coated rods in accordance with MIL-STD-810B, Method 509, Procedure 1. During testing there were two fixture failures unrelated to the coatings which delayed completion of the tests. Testing was successfully completed with no unallowable fluid leakage and no wear on the coatings. The actuator also successfully passed the temperature cycling test and the salt fog corrosion test.

F-15 Pitch/Roll Channel Assembly: A contract has been issued to Moog, the OEM for the component, for rig testing. It is anticipated that HVOF WC/CoCr coatings will be applied to the piston for the test.

T-38 Aileron Actuator: A contract was issued to Smiths Aerospace to perform the qualification testing. Pistons were coated with HVOF WC/CoCr and were assembled into a complete actuator by Smiths. This test was successfully completed and the report is currently being written. There were some failures of piston seals (seals which do not contact the coated surfaces and were likely due to fixture configuration) which may warrant additional testing.

C-130 Ramp Actuator: Two piston rods were coated with HVOF WC/CoCr. Testing was performed by ARINC and OC-ALC/ENFLL in the OC-ALC Engineering Laboratory. It consisted of a 20,000 cycle endurance test and a temperature test in which each actuator was subjected to a cold soak at -65ºF and then cycled 5 times while still at that temperature. Excessive leakage was observed with the initial seals that were used. These were replaced with alternative seals which performed well. Overall, it was concluded by OC-ALC that the WC/CoCr coatings passed the qualification test when using the correct seals.

C/KC-135 Main Landing Gear Actuator: Two piston rods were coated with HVOF WC/CoCr and were assembled into two test actuators. The testing was performed by ARINC and OC-ALC/ENFLL in the OC-ALC Engineering Laboratory. For endurance testing, each actuator was subjected to 20,000 cycles and for temperature testing each actuator was subjected to a cold soak at -65°F, then cycled 5 times while still at that temperature. Actuator A contained an elastomeric O-ring with backups and Actuator B contained a spring-energized Coorstek Rod Seal with a Coorstek Scraper. The O-ring configuration failed the endurance test due to excessive leakage. The spring-energized seal passed the endurance test with very little leakage. The O-ring configuration failed the temperature test due to excessive leakage whereas the spring-energized seal successfully passed the test with no leakage. Overall, it was concluded by OC-ALC that the HVOF WC/CoCr coatings passed the qualification test if the correct seals were used.

C/KC-135 Main Landing Gear Door Actuator: It was decided by OC-ALC that the HVOF WC/CoCr coatings would be considered qualified on this component due to the successful results of the testing on the main landing gear actuator.

C/KC-135 Aileron Snubber: HVOF WC/CoCr coatings were applied to two pistons and they were assembled into two actuators. Testing was performed by ARINC. For endurance testing, each actuator was subjected to 21,200 cycles and for temperature testing each actuator was subjected to a cold soak at -65ºF, then cycled 5 times while still at the same temperature. Actuator A, with O-ring and backup rings, completed 21,200 cycles with zero leakage. Actuator B, with a VLS Seal, completed 21,200 cycles with 8 total drops of fluid which was considered acceptable. It was noted that the piston rod from this actuator had a small circumferential scratch. For the temperature testing, both actuators completed the test with zero leakage.

In addition to the Air Force testing, NAVAIR Patuxent River performed testing on a F/A-18 C/D Stabilator Actuator in which the normally EHC-plated rod was instead coated with HVOF WC/CoCr on the shorter external end and WC/17Co on the longer internal end. Both coatings

were ground to an 8-16 microinch Ra finish and then superfinished to less than 2 microinch Ra. Testing was performed on the same rig as was used for the functional rod/seal testing described in Section 3.6. It consisted of 10 layers of testing, with each hour consisting of 3 minutes full stroke, 9 minutes of half-strokes and 48 minutes of dither strokes. One layer was conducted at 275°F, two layers at 250ºF, three layers at 225°F and four layers at 185ºF. The actuator was chilled to -40ºF each night to evaluate static leakage. The results of these tests were that the fluid leakage was the same for the HVOF-coated rod as for the EHC-coated rod, with fewer scratches observed on the HVOF-coated rod at the end of the testing.

4.3 DATA EVALUATION AND TECHNOLOGY COMPARISON

Materials Testing – Fatigue

For 4340 and PH15-5, the fatigue performance of the HVOF coatings was equal or superior to that for EHC. The only spalling seen with HVOF coatings (other than one sample with WC/CoCr at runout) was for Cr_3C_2/NiCr at high stress. Other HVOF coatings developed fine circumferential cracks at high cycles. This type of coating cracking has been observed to occur in HVOF-coated landing gear without causing deleterious performance results, such as leakage, corrosion or seal damage. For these base materials, it was concluded that the fatigue data show that the HVOF coatings meet the JTP acceptance criterion of being better than or equal to hard chrome.

For Ti-6Al-4V, the EHC coatings showed spalling on almost all specimens. Titanium alloys are known to be very hard to plate because of the difficulty in activating them effectively. Inadequate activation produces a plating with poor adhesion. The EHC spalled well before failure, with the coating delaminating over most of its surface. Clearly this type of coating would not be acceptable on aerospace components. The fatigue curve for the EHC specimens was essentially the same as for the uncoated material, presumably at least in part because the specimens were effectively uncoated once the coating spalled.

The relatively poor spalling performance of the HVOF coatings on T-6Al-4V is believed to be due to the surface preparation prior to coating. The method agreed to in the JTP avoided grit blasting (which is standard practice in HVOF coating) so as to prevent grit embedding in the surface. Subsequent discussions have indicated that many thermal spray facilities do grit blast, but at a lower gas pressure (lower particle velocity) and at an angle, both of which tend to prevent grit embedding. As a result they are able to achieve good adhesion of the HVOF coating in production on Ti alloy substrates such as flap tracks.

The data for Ti-6Al-4V demonstrate the need for development of proper grit blasting procedures, which are clearly essential for proper adhesion. Even with this poor preparation, however, the HVOF coatings spalled only at the top and bottom of the curve (high stress or high cycles), showing cracking but no spalling over most of the range. Both the EHC and HVOF data for Ti-6Al-4V are unreliable because of inadequate surface preparation. Even with this, WC/CoCr performed well except at high load or high cycles ($>10^6$). If HVOF (especially coatings other than WC/CoCr) is to be considered for use on titanium alloy actuator components, the fatigue data should be retaken with adequate surface preparation for both the EHC and the thermal spray.

Materials Testing – Corrosion

The corrosion performance of the EHC coatings was somewhat better than for any of the HVOF coatings on the three substrate materials, results that are similar to previous B117 salt fog corrosion studies comparing the performance of various HVOF coatings to EHC coatings. In this study, the results were not consistent between the panels and rods, with the T-400 coatings generally showing the best performance on the panels and the worst performance on the rods. The performance of the WC/CoCr coatings was significantly better on the rods than on the panels. In addition, it appeared that superfinishing slightly improved the corrosion performance of the WC/CoCr.

In general, it can be concluded that the HVOF coatings investigated in this study did not meet the acceptance criteria. The results obtained in this project are consistent with those obtained in previous HVOF thermal spray chrome replacement projects [3,4,5] where most of the HVOF carbide or tribaloy coatings demonstrated inferior performance to EHC coatings, especially on low-alloy steel substrates, in cabinet salt fog testing. However, as pointed out in the landing gear report [3], the cabinet salt fog test results have been contradicted by other types of tests. For example, HVOF WC/17Co coatings demonstrated significantly superior performance to EHC coatings on 4340 steel in three-year beach atmospheric corrosion testing. In addition, it was reported that field trials of a WC/17Co-coated P3 main landing gear piston showed no evidence of corrosion or other degradation after four years service [3]. As of the date of this report, that piston is still in service after six years and more than 6400 landings with no evidence of coating degradation.

Materials Testing – Fluid Immersion

Based on the results of the immersion tests, all coatings appear to be resistant to attack by the fluids, with the exception of bleach. Sodium hypochlorite attacks and degrades the cobalt-containing coatings. The HVOF Tribaloy-400 coatings experienced small but statistically significant mass loss after immersion in some of the test fluids and therefore could be ill-suited to applications where they might be exposed to strong cleaning agents or other reactive chemicals. HVOF Cr_3C_2/NiCr and WC/CoCr coatings can both be expected to resist common liquids during service and maintenance, but procedures should emphasize the danger of exposing WC/CoCr to sodium hypochlorite bleach, and measures should be implemented to guard against its use.

Given how aggressively chlorine bleach attacked the cobalt-containing coatings, it is recommended that an extensive investigation of sodium hypochlorite affects on HVOF coatings be conducted. A test procedure should be developed to investigate ramifications, and a test matrix should be developed for different concentrations of sodium hypochlorite and exposure times as well as different exposure conditions.

Materials Testing – Environmental Embrittlement

Since none of the specimens fractured during the test, it was concluded that environmental embrittlement is not an issue for either EHC or the three types of HVOF coatings on 4340, PH15-5 or Ti-6Al-4V.

Functional Rod/Seal Testing

For Phase I testing, Table 9 provides an overall ranking of the various rod/seal configurations based on fluid leakage and seal and coating wear. Based on these results, it is evident that the performance of the HVOF coatings generally exceeded that of the EHC coatings.

Table 9. Overall Ranking of the Various Rod/Seal Configurations from Phase I Test.

Ranking	Rod/Seal Configuration
Superior Performance	HVOF 20-22 Ground w/ SF with MIL-P-83461 O-ring/Cap HVOF As-Ground with Spring Energized PTFE HVOF 20-22 Ground w/ SF with Spring Energized PTFE HVOF 8-10 Ground w/ SF with Spring Energized PTFE HVOF As-Ground with MIL-P-83461 O-ring/Cap HVOF 8-10 Ground w/ SF with MIL-P-83461 O-ring/Cap
Fair Performance	* HVOF 8-10 Ground w/ SF with MIL-P-83461 O-ring/2 Backup Rings HVOF As-Ground with Fluorosilicon O-ring/PTFE Cap * Chrome with MIL-P-83461 O-ring/2 Backup Rings * HVOF As-Ground with MIL-P-83461 O-ring/2 Backup Rings HVOF 20-22 Ground w/ SF with Fluorosilicon O-ring/PTFE Cap
Worst Performance	Chrome with MIL-P-83461 O-ring/Cap Chrome with Fluorosilicon O-ring/PTFE Cap Chrome with Spring Energized PTFE HVOF 8-10 Ground w/ SF with Fluorosilicon O-ring/PTFE Cap

Based on the results from Phase II testing as presented in Table 8, it is apparent that a superfinished surface provides significantly better performance compared to a ground surface. With respect to a comparison between tape (identified as “film” in the table) and stone superfinishing, on average it appears that the tape superfinished surfaces perform slightly better.

Component Tests

Overall, actuators with HVOF WC/CoCr-coated rods were found to perform as well as or better than those with EHC-coated rods, although in some cases different seals were required. The following summarizes the assessments of the completed tests performed on each component.

C130 Rudder Booster Actuator: It was concluded from these tests that the HVOF coatings provided at least equivalent and potentially superior performance to EHC and therefore service testing could be initiated.

B-1 Horizontal Stabilizer: No service tests are planned for this actuator. Drawing updates have been completed to provide for use of the HVOF WC/CoCr coatings and Tech Order and stocklist

updates are in progress. This actuator, using HVOF WC/CoCr, is ready for implementation. It is expected that other B-1 flight control actuators will be qualified by similarity.

A-10 Aileron: With the successful completion of the delta qualification tests, it is expected that actuators containing HVOF-coated components will begin service testing sometime in 2006. It is expected that the A-10 rudder and elevator actuators will be able to be qualified by similarity.

T-38 Aileron Actuator: This test was successfully completed and the report is currently being written. There were some failures of piston seals (seals which do not contact the coated surfaces and were likely due to fixture configuration) which may warrant additional testing.

C-130 Ramp Actuator: It was concluded by OC-ALC that the HVOF WC/CoCr coatings passed the qualification test if the correct seals were used. This actuator was designated for service testing. It was expected that the WC/CoCr coatings would be qualified on the C-130 Aft Cargo Door Actuator by similarity.

C/KC-135 Main Landing Gear Actuator: Overall, it was concluded by OC-ALC that the HVOF WC/CoCr coatings passed the qualification test if the correct seals were used. This actuator was designated for service testing. It was expected that the WC/CoCr coatings would be qualified on the E-3 main landing gear actuator by similarity.

C/KC-135 Aileron Snubber: The HVOF WC/CoCr coatings passed the qualification test and this actuator was designated for service testing. It was anticipated that the C/KC-135 rudder and elevator snubber actuators could be qualified by similarity.

For the F/A-18 C/D Stabilator Actuator, an Engineering Change Proposal was validated for replacement of EHC with HVOF WC/Co or WC/CoCr. As of the date of this report, it is not clear if the HVOF coatings will actually be implemented into repair operations.

5.0 COST ASSESSMENT

5.1 COST REPORTING

A detailed cost/benefit analysis (CBA) for replacement of EHC plating with HVOF thermal spray was conducted at a facility that performs repair and overhaul of aircraft components including landing gear and hydraulic actuators. The complete CBA is presented in the Final Report for this project [7] and a summary is presented here. Data collection at the facility and financial analyses of the data were performed using the JG-PP Environmental Cost Analysis Methodology (ECAM) [8]. The ECAM integrates activity-based costing concepts and provides standard economic indicators, including net present value (NPV), payback period, and internal rate of return (IRR). The labor rate used in this analysis is $65 per hour; this is considered a fully burdened rate and is often used as a default rate for DoD cost benefit analyses. This analysis does not include the project costs associated with qualification testing of the process.

Three scenarios were developed and analyzed for this CBA. The first scenario (Base Scenario) considers both landing gear and actuator components. Scenario 2 evaluates just actuator components only. It should be noted that actuator components only account for 5% of total chrome electroplating at the facility. In an attempt to isolate these costs, 5% of the total electroplating costs were used. Since these costs cannot be easily separated, this method provides only a rough estimate of actual actuator plating costs. Scenario 3, which includes both landing gear and actuators, also includes expected capital expenditures for the plating department. This scenario assumes that these expected costs could be avoided if the alternative process was implemented. The Base Scenario and Scenario 2 do not include these capital expenditures in the analysis as they are considered sunk costs due to expenditures already being scheduled. In addition, alternative cases were analyzed for the Base Scenario. Case 1 analyzed the impact of expected increased service life of the landing gear and actuators with HVOF coatings. Case 2 analyzes the potential impact of proposed OSHA regulations for chromium exposure. (Note that the new hex-Cr PEL had not been issued at the time the CBA was performed).

A site visit was conducted on December 17-19, 2002 to collect baseline data on the hard chrome plating process at the repair facility. During the site visit, interviews were held with process engineers, plating operators, plating supervisors, program managers, environmental staff, and other employees throughout the facility. The information gathered during the site visit was supplemented with additional correspondence following the visit.

All capital costs for the baseline process were considered to be sunk costs; therefore the Base Scenario and Scenario 2 did not include any capital expenditures. Two large capital expenditures are budgeted for the plating shop in the near future. This includes an anode upgrade and testing project in year one, which includes $350,000 for materials and labor consisting of 0.5 full time equivalents (FTE) for that year. Also included is a plating shop upgrade expected to cost $1,500,000 in year two and year three. Scenario 3 considers these costs to be avoidable if the HVOF systems are implemented, and therefore they are included as baseline costs.

Annual operating costs were compiled that included labor, fixturing, laboratory analysis, materials, chemicals, utilities, waste disposal and environmental management costs. For the combined landing gear and actuator operations, the total annual operating cost was $5.3 million. For just the actuator operations, the annual operating cost was $751,000.

For replacement of the EHC operations with HVOF, data was collected from the repair facility and HVOF vendors, including the cost of powder, cost of gases, deposition rate, deposition efficiency, equipment component lifetimes, and laboratory analysis requirements. A number of assumptions were made in the analysis, including:

- Approximately 80% of the landing gear components and 100% of the actuator components currently EHC-plated can be transitioned to HVOF, requiring 20% of the landing gear components to still be chrome-plated
- HVOF labor requirements were one FTE per booth for spraying and two FTE total for assisting with the process
- Ten of 15 plating tanks will be decommissioned after HVOF implementation
- Two out of three sodium hydroxide stripping tanks will be decommissioned after HVOF implementation
- The increased cost of diamond grinding wheels for HVOF will be offset by reduced time of grinding; therefore these costs were not included in the analysis
- The chrome plating operation is not a production bottleneck; therefore implementation of HVOF and the resulting reduced throughput would not result in any cost savings other than the elimination of overtime costs
- Since reduced throughput would not result in a cost savings, inventory costs were not calculated

The cost for deconstruction of the ten process tanks is expected to be roughly equal to the salvage value of the equipment; therefore, this cost was not captured in this analysis.

For the Base Scenario the following capital equipment costs were considered: $1,857,580 in HVOF equipment costs, $100,000 in installation costs, $740,000 in facility expansion costs, $10,000 in stripping rectifier costs and $920,930 in grinding equipment costs; all costs are expensed in year zero. An additional $740,000 in facility expansion costs is expensed in year one. Additional costs include training costs of $114,400 and a $5,000 cost for modification of the Clean Air Act permit expensed in year 0. For Scenario 2 the following capital equipment costs are considered: $535,000 in HVOF equipment costs, $75,000 in installation costs, $740,000 in facility expansion costs, $10,000 in stripping rectifier costs and $265,200 in grinding equipment costs; all costs are expensed in year zero. Additional costs include training costs of $33,800 and a $5,000 cost for modification of the CAA permit expensed in year zero.

All equipment costs were expensed using straight-line depreciation over ten years. All facility construction costs were expensed using straight-line depreciation over 20 years. Useful life and salvage values were estimated using Air Force Instruction 38 203 as guidance.

The annual labor, material, utility and waste disposal costs for the HVOF thermal spray process for landing gear and actuators were calculated to be $3.7 million. This assumes that 20% of the

parts will continue to be chrome plated. The annual operating costs for just actuators was calculated to be $554,000. This assumes 100% transition to HVOF for these components.

In addition to the scenarios above, the impact of other variables on the coating process was considered. Case 1 analyzed the impact of increased service life of the landing gear and actuators expected to be realized with implementation of the HVOF coating. Case 2 analyzed the potential impact of proposed (at the time of the CBA) OSHA regulations for worker exposure to chromium. Both of these cases have been applied to the Base Scenario only, (e.g., landing gear and actuators) with no expected elimination of pending electroplating upgrade costs.

<u>Case 1</u>: It is estimated that a constant throughput of chrome-plated parts will come in for repair and will be recoated using HVOF for a minimum of five years. However, based on the anticipated extension in service life that HVOF is expected to provide, components previously coated with HVOF that return to the depot may not necessarily be processed. If it is agreed that HVOF thermal sprayed components do not have to be stripped for inspection upon return to the depot (unless required for repair purposes), the number of landing gear and actuator parts processed annually will decrease over time. The following assumptions were used to analyze the cost benefit of this scenario.

A. Years 1-5: All landing gear and actuators components coming into the depot have chrome plating that is stripped for inspection and repair purposes. Applicable components are recoated using HVOF thermal spray at the current throughput rate of 9,755 parts per year.

B. Years 6-10: 50% of the components processed are chrome-plated parts, which are stripped, inspected, repaired, and recoated using HVOF thermal spray. It is assumed that the remaining 50% of the parts were previously coated using HVOF. It is estimated that 25% of these components (12.5% of the total throughput) will be stripped, inspected/repaired, and recoated using HVOF. The remaining components (37.5% of the total throughput) will require no processing. Thus, the total number of parts processed annually will be 6,097 components.

C. Years 11-15: All components coming into the depot were previously coated using HVOF. Of these, 25% will be stripped, inspected/repaired, and recoated using HVOF thermal spray. The total number of parts processed annually will be 1,524 components.

As this case is applied to the Base Scenario, the capital costs are the same as those identified for that scenario. The annual labor, material, utility and waste disposal costs for this case for combined landing gear and actuator components were calculated to be $2.1 million for years 1-5, $1.3 million for years 6-10 and $530,000 for year 11-15.

<u>Case 2</u>: This case considered additional costs associated with a lowering of the hex-Cr PEL to both 5 and 0.5 $\mu g/m^3$. Since the actual revised PEL as issued by OSHA in February 2006 was 5 $\mu g/m^3$, only that case will be discussed here. The capital costs associated with engineering control upgrades associated with the new PEL were estimated to range from 0 to $50,000, with a most likely value of $32,000. The increased operating costs were estimated to range from 0 to

$20,000, with a most likely value of $10,800. Increased ESOH costs, including training, PPE, monitoring and medical surveillance, were estimated to be $23,200.

5.2 COST ANALYSIS

The ECAM includes a financial analysis that was performed using the Pollution Prevention Financial Analysis and Cost Evaluation System (P2/FINANCE) software. The P2/FINANCE software generates financial indicators that describe the expected performance of a capital investment. A brief explanation on interpreting these financial indicators is provided, as are the results of the financial analyses for the implementation of HVOF thermal spray for landing gear and actuators.

To measure the financial viability of this project, three performance measures for investment opportunities were used: net present value (NPV), internal rate of return (IRR), and payback period. The NPV is the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. The IRR is the discount rate at which NPV is equal to zero. NPV and IRR account for the time value of money, and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 2.7% discount rate was used for this financial evaluation, which is consistent with the (Office of Management and Budget) OMB Circular Number A-94 and the ECAM. The payback period is the time period required to recover all of the capital investment with future cost savings. Guidelines for these performance measures are listed in Table 10.

Table 10. Summary of Investment Criteria.

Criteria	Recommendations/Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
Highest NPV	Maximum value to the facility
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable
Shortest payback period	Fastest investment recovery and lowest risk

Adapted from ECAM Handbook.

A summary of the financial evaluation for implementing HVOF to replace hard chrome electroplating of landing gear and actuators is listed in Table 11, Table 12 and Table 13 for the Base Scenario and Scenario 2 and Scenario 3, respectively.

Table 11. Base Scenario: Results of Financial Evaluation (landing gear and actuators without expected plating capital expenditures).

Financial Indicator	5-yr	10-yr	15-yr
NPV	$3,084,200	$9,694,900	$15,780,900
IRR	25.7%	36.4%	37.9%
Discounted Payback	2.88 years		

Table 12. Scenario 2: Results of Financial Evaluation (actuators only without expected plating capital expenditures).

Financial Indicator	5-yr	10-yr	15-yr
NPV	($797,900)	($39,800)	$710,500
IRR	(16.3%)	2.2%	7.8%
Discounted Payback	10.31 years		

Table 13. Scenario 3: Results of Financial Evaluation (landing gear and actuators with expected plating capital expenditures).

Financial Indicator	5-yr	10-yr	15-yr
NPV	$4,887,500	$11,497,100	$17,582,300
IRR	40.0%	47.2%	48.0%
Discounted Payback	2.10 years		

The Base Scenario was used as the basis of two additional analyses. Case 1 takes into account the potential increased service life of HVOF coating and consequently a declining throughput of components needing coated. Table 14 is a summary of the financial evaluation for implementing HVOF to replace hard chrome electroplating of landing gear and actuators for a declining throughput.

Table 14. Case 1: Results of Financial Evaluation for Increased Service Life of Components with HVOF Coatings.

Financial Indicator	5-yr	10-yr	15-yr
NPV	$3,082,300	$12,973,700	$24,717,800
IRR	25.5%	39.7%	41.8%
Discounted Payback	2.88 years		

Case 2 accounts for the additional cost avoidance that may be realized under a reduction of the hex-Cr PEL. Due to the difficulties associated with predicting the economic impact of a proposed regulation, Monte Carlo simulation was used to forecast the potential impact. Using Monte Carlo simulation, key variables are defined within a given range and distribution profile instead of a single (uncertain) value. The output shows the range of possible results and degree of certainty that any desired outcome can be achieved. During the Monte Carlo simulation, 5,000 trials (possible combinations of variable assumptions) were run for each case study. The results of the Monte Carlo simulation for the 15-year NPV for a PEL of 5 $\mu g/m^3$ (Case 2) ranged from $16.4 million to $16.7 million, with a mean value of $16.5 million.

A summary of the cost benefit indicators for Case 2 is presented in Table 15. All data are mean values.

Table 15. Case 2: Results of Financial Evaluation for Hex-Cr PEL of 5 µg/m^3.

Financial Indicator	Cost Benefit
15-Year NPV	$16,522,000
IRR	39.6%
Discounted Payback	2.76 years

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The results of the CBA indicated that HVOF is an economically feasible alternative for chromium electroplating for landing gear and actuators at the repair facility used in the analysis.

A base scenario, two additional scenarios and two cases applied to the base scenario all showed an economic benefit with implementation of HVOF for landing gear and actuators. Analysis of the Base Scenario (landing gear and actuators) indicated an expected payback of under 3 years. The 15-year net present value is \$15.8 million and the 15-year IRR is 38%. The analysis of scenario 2 (actuators only), which accounts for just 5% of the chrome plating, indicated an expected payback of 10 years. This scenario did not show a positive NPV until year 11; the 15-year NPV was \$727,000 and the corresponding IRR is 8.2%. Scenario 3 (landing gear and actuators) also includes expected capital expenditures for the plating department. This scenario assumed that these expected costs could be avoided if the alternative process was implemented. Scenario 3 had a 15-year NPV of \$17.6 million, a corresponding IRR of 48.2% and a payback of 2 years. The primary cost driver for these scenarios is the reduced labor costs associated with HVOF; a secondary cost driver is the expected reduction in environmental management costs associated with HVOF coating.

The above scenarios represent the expected cost impact of implementing HVOF using the same repair schedule and under present environmental regulatory conditions. However, for a thorough analysis, two additional cases were considered. Case 1 considered the expected impact on service life of the components after HVOF implementation. Since HVOF has reportedly shown wear resistance of up to four times as great as that of electroplated chrome, it is expected that the repair schedule could be reduced after HVOF implementation. Therefore Case 1 analyzed a declining throughput of components; this scenario is expected to have a 15-year NPV of \$24.8 million with a corresponding IRR of 41.9%. The payback period is expected to be 2.87 years. The primary cost driver for Case 1 is the reduction in overall operating costs due to the increased service life of the components with HVOF coating.

Case 2 analyzed the potential impact of the new OSHA PEL of 5 $\mu g/m^3$. For this analysis, Monte Carlo simulation was used to allow input of a range of capital equipment costs. The 15-year NPV for Case 2 ranged from \$16.3 million to \$16.7 million, with a mean value of \$16.5 million. Mean values for IRR and payback are 39.6% and under 3 years respectively.

Economic studies of HVOF implementation at other facilities have shown a range of results, indicating that the economic feasibility of HVOF implementation is highly dependent on site-specific details. The actual economic effects at facilities will vary depending on the actual throughput converted, future workloads, and other factors specific to each facility.

6.2 PERFORMANCE OBSERVATIONS

For the materials testing, substrates were 4340 high strength steel, (180-200 ksi UTS), PH15-5 stainless steel (155 ksi UTS) and Ti-6Al-4V (130 ksi UTS). HVOF coatings were WC/10Co4Cr,

Cr_3C_2/20(80Ni-20Cr) and Tribaloy 400 (T-400, nominal composition 57Co-28.5Mo-8.5Cr-3.0Ni-3.0Si). The following summarizes the results of the materials tests.

- Fatigue: All HVOF coatings on 4340 and PH15-5 steel were equal to or better than EHC, with T-400 having significantly better fatigue. There was some cracking of the HVOF coatings at the highest loads as well as at the highest cycles. Spalling of the HVOF coatings occurred on 4340 at the highest load (160 ksi) and at the highest cycles (9.5 million cycles). There was cracking, but no spalling, on the PH15-5 specimens. The data on Ti-6Al-4V were unreliable since neither the EHC nor the HVOF coatings adhered properly – EHC because of inadequate activation and HVOF because the surface was not grit blasted so as to avoid embedding grit particles. All the EHC coatings on Ti-6Al-4V spalled, while the HVOF coatings also spalled over some of their range.
- Salt Fog Corrosion (ASTM 1000 hour B117): As in previous tests, the EHC coatings in general provided somewhat better appearance rankings than HVOF coatings. Thicker EHC or HVOF coatings did not in general provide any better protection. Both rods and flat panels were evaluated, with no consistent performance differences between them. Previous HVOF EHC replacement projects determined that there is very poor correlation between the standard B117 cabinet testing of HVOF and EHC coatings and their actual performance in beach exposure and in service. Since the B117 corrosion behavior on the substrates in this testing is similar to what has been seen in other evaluations, it is expected that the service performance of HVOF coatings on these substrates is likely to be better than that of EHC, just as it is on 300M and fully hardened 4340.
- Fluid Immersion: The coatings were tested for weight loss and roughening in a wide variety of commonly-used cleaners, etchants, hydraulic fluids, fuels and other chemicals likely to be encountered during MRO or in service. WC/CoCr and Cr_3C_2/NiCr were not affected by any of these chemicals, while T-400 showed slight attack by strong cleaners and reactive chemicals. The one exception was that the Co-containing coatings, WC/CoCr and T-400, were both strongly attacked by bleach (sodium hypochlorite). Bleach is not an approved MRO chemical, but is sometimes used as a disinfectant on commercial aircraft during disease outbreaks. Cr_3C_2/NiCr was unaffected.
- Environmental Embrittlement (200 hour ASTM F519): None of the coatings, including EHC, caused environmental embrittlement (re-embrittlement) in DI water or 5% NaCl solution.

Functional Rod-Seal Testing was performed by NAVAIR Patuxent River using HVOF WC/CoCr with different surface finishes, using actuator speeds and temperatures intended to simulate service conditions. Several seals from different manufacturers were tested – O-ring with capstrip, O-ring with two backup rings, fluorosilicone O-ring with PTFE cap and spring energized PTFE. In almost all cases the HVOF coatings gave significantly less leakage than the EHC, the only exception being a seal system of an O-ring with two backups, where the performance of HVOF and EHC was the same. Surprisingly, the ground (not superfinished) rods had the least leakage of all. However, they did smooth out over time, whereas the superfinished

rods showed only very faint scratches. (The EHC coated rods showed considerable scratching.) There was very little seal damage or rod damage, especially when using superfinished coatings. Tape superfinished coatings performed slightly better than stone superfinished. Overall the best performance was for a superfinished rod with either a MIL-P-83461 O-ring with PTFE cap strip or spring energized PTFE seals with backup ring.

Component testing and qualification of actuators with HVOF-coated rods was carried out by the Oklahoma City Air Logistics Center. Flight control actuators, utility actuators and snubbers were tested, with test components chosen to permit qualification of additional components by similarity. Overall, actuators with HVOF-coated rods were found to perform as well as or better than those with EHC-coated rods, although in some cases different seals were required. A number of actuators have passed rig tests and are going into service testing. Actuators tested were: C130 Rudder Booster Actuator, A-10 Aileron Actuator, C/KC-135 Aileron Snubber (passed testing, to be service tested); B-1 Horizontal Stabilizer (endurance testing successful, no service tests needed, drawings updated, Tech Order and stocklist updates in progress); B-1 Pitch/Roll SCAS (testing in progress); F-15 Pitch/Roll Channel Assembly (to be tested); T-38 Aileron (testing successful); C-130 Ramp and C-KC-135 Main Landing Gear Actuators (passed testing with change to seal specification, to be service tested); C/KC-135 Main Landing Gear Door (qualified for service testing); Navy F/A-18 C/D Stabilator

6.3 SCALE-UP

Most of the Air Force and Navy repair facilities that overhaul hydraulic actuators already have HVOF systems including two each at OO-ALC, NADEP-JAX and NADEP Cherry Point. These HVOF systems are full-production facilities with fixturing for manipulation of various types of components and robots on which the HVOF spray guns are mounted. The only issue is the number of spray booths required to replace all of the chrome plating operations for which HVOF is amenable. OO-ALC is projecting a total of 10 spray booths, four considered small, four medium, and two large for processing different size components. These spray booths would be used for processing both landing gear and actuator components. NADEP-JAX has not projected the total number of spray booths required, but does plan on acquiring more as the number of components approved for HVOF processing increases. All three of these depots have developed procedures for surface preparation prior to coating deposition and for grinding of the coatings subsequent to deposition. Therefore, there are no scale-up issues associated with implementation of this technology.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Based on the results of the materials testing, functional rod/seal testing and delta qualification testing, the Air Force is proceeding with in-service testing of actuators containing HVOF-coated pistons, with the ultimate goal of implementing the technology on all Air Force actuators. This should ultimately lead to the elimination of hard chrome plating on all AF actuators. At a facility such as OO-ALC, there will still be the issue of replacing hard chrome on non-line-of-sight (NLOS) surfaces such as internal diameters on landing gear cylinders. If a NLOS alternative can be successfully demonstration and validated, then EHC plating could be entirely eliminated from that repair facility.

6.5 LESSONS LEARNED

In attempting to qualify and implement a new technology on safety-of-flight components such as hydraulic actuators for flight control surfaces, it is essential to involve the entire stakeholder community from the outset and identify important areas of concern. Contributions from program offices, system support offices, depot engineers, and OEMs were made toward development of the JTP and all results, positive and negative, were presented to them for evaluation and consideration. When an unexpected issue arose it was again important to involve the stakeholder community and obtain their criteria for acceptable performance. There must be flexibility (both programmatic and financial) built into any project of this type so that unplanned testing can be conducted to address unforeseen issues.

6.6 END-USER/OEM ISSUES

One of the key end user/OEM issues is the availability of standards and specifications related to the powder used for HVOF coatings, application procedures for the coatings, and grinding procedures for the coatings. The HCAT has worked with the SAE Aerospace Metals Engineering Committee to develop four separate specifications in these areas. Those related to powder, coating deposition and grinding were completed and forwarded to SAE Aerospace Materials Committee B. The following are the designations:

> AMS 2448 – "Application of Tungsten Carbide Coatings on Ultra-High-Strength Steels, High-Velocity Oxygen/Fuel Process" issued in August 2004
>
> AMS 2449 – "Grinding and Superfinishing of Tungsten Carbide Coatings Deposited Using High-Velocity Oxygen/Fuel Process" issued in August 2004
>
> AMS 7881 – "Tungsten Carbide-Cobalt Powder, Agglomerated and Sintered" issued in April 2003
>
> AMS 7882 – "Tungsten Carbide-Cobalt Chromium Powder, Agglomerated and Sintered" issued in April 2003

Although AMS 2448 was developed principally for landing gear, the procedures are applicable to other components such as on hydraulic actuator components. In fact, the parameters defined in AMS 2448 were used for application of WC/CoCr on the Actuator JTP materials specimens. All of these specifications can now be utilized by any manufacturing or overhaul depot and their use will result in consistency between facilities with respect to coating properties.

If other coatings that were evaluated in the actuator materials testing are intended to be used, then additional specifications will have to be developed. This was beyond the scope of this project.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The principal environmental and worker safety issues associated with HVOF thermal spraying are air emissions containing overspray particles and the noise of the gun itself. All of the depots involved in the HCAT project already had other types of thermal spray equipment in operation,

such as flame or plasma spray, and therefore they had the appropriate air handling equipment (e.g., exhaust hoods, bag houses) available and also had the appropriate air permits to cover operation of the HVOF systems. With respect to noise, all of the HVOF systems are installed in sound-proof booths and are computer-controlled. Therefore, no operator is exposed to the noise of the HVOF gun.

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3. Bruce D. Sartwell et al., "Validation of HVOF WC/Co Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Aircraft Landing Gear." Naval Research Laboratory Report NRL/MR/6170-04-8762, 31 March 2004.

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5. Bruce D. Sartwell et al., "Replacement of Chromium Electroplating on Gas Turbine Engine Components Using Thermal Spray Coatings," Naval Research Laboratory Report NRL/MR/6170-05-8890, 20 July 2005

6. Joint Test Protocol, "Validation of HVOF Thermal Spray Coatings as Replacements for Hard Chrome Plating on Hydraulic/Pneumatic Actuators," DOD Hard Chrome Alternatives Team, 2 August 2004

7. Final Report, "Validation of HVFO Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Hydraulic/Hydraulic Actuators," DOD Hard Chrome Alternatives Team, 27 July 2006

8. "Environmental Cost Analysis Methodology (ECAM) Handbook," Environmental Security Technology Certification Program (ESTCP) Validation Tasks, Contract No. DAAA21-93-C-0046, Task NO. 098, CDRL No. A013, Concurrent Technologies Corporation, Johnstown, PA, January 7, 1999

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APPENDIX A

POINTS OF CONTACT

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